JOURNAL OF GEOLOGY

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

THE CAMBRIDGE UNIVERSITY PRESS
LONDON

THE MARUZEN-KABUSHIKI-KAISHA
TOKYO, OSAKA, KYOTO, FUKUOKA, SENDAI

THE MISSION BOOK COMPANY
SHANGHAI

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JOURNAL OF GEOLOGY

A Semi-Quarterly Magazine of Geology and Related Sciences

VOLUME XXVII

JANUARY–DECEMBER, 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

Published
February, March, May, June, August, September,
November, December, 1919

Composed and Printed By
The University of Chicago Press
Chicago, Illinois, U.S.A.

Contents of Volume XXVII

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VOLUME XXVII NUMBER

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

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THE MISSION BOOK COMPANY, SHANGHAI

ebruary 1919 Vol. XXVII, No. 1

HE JOURNAL OF GEOLOGY

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The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

The following are authorized to quote the prices indicated:

For the British Empire: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, 18*s*. 8*d*. each; single copies, including postage, 3*s*. 2*d*. each.

For Japan and Korea: The Maruzen-Kabushiki-Kaisha, 11 to 16 Nihonbashi Tori Sanchome, Tokyo, Japan. Yearly subscriptions, including postage, Yen 9.00 each; single copies, including postage, Yen 1.50 each.

For China: The Mission Book Company, 18 Peking Road, Shanghai. Yearly subscriptions $4.00; single copies 65 cents, or their equivalents in Chinese money. Postage extra, if mailed direct outside of Shanghai, on yearly subscriptions 53 cents, on single copies 11 cents.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit. Deliveries are not guaranteed within the war zones of Europe, nor in other countries where transportation is disturbed by conditions incident to war.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations

VOLUME XXVII NUMBER 1

THE

JOURNAL OF GEOLOGY

JANUARY-FEBRUARY 1919

THE GEOLOGY OF NORTH DAKOTA

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INTRODUCTION

The geology of North Dakota is comparatively simple. The geological formations are not as numerous or of such great variety as in many states, and the strata have undergone but little deformation since they were deposited. They are for the most part practically horizontal or have only a gentle dip. Metamorphism has produced little or no change in the rocks, and, except for the deeply buried granite near the eastern borders of the state, there have been no intrusions or extrusions of igneous material. The rocks are chiefly clays, shales, and sandstones belonging to the Cretaceous and Tertiary periods, overlain in most places by the drift deposits of the Pleistocene. The surface features of about two-thirds of the state are therefore those of a gently rolling to rough drift plain. The flat lacustrine plain of the Red River Valley occupies a strip 25 to 35 miles wide along the eastern border, while west and south of the Missouri River the drift mantle is too thin to affect the topography to any great extent. This large area beyond the Missouri everywhere shows evidence of long-continued erosion, with its numerous stream valleys, buttes, mesas, and badlands.

THE PRE-CAMBRIAN GRANITE

Many deep wells in the Red River Valley have reached granite, and these show that beneath the drift and older formations the valley is underlain by crystalline rock which is probably of Archean age, though like some of the Minnesota granite it may possibly be Keweenawan. The granite is struck at depths ranging from 255 to 470 feet, and its surface is quite uneven. It is overlain in some places by glacial drift, in others by Cretaceous shale and sandstone, and in the northern portion of the valley by Paleozoic strata.

In going from south to north in the valley the granite has been encountered in wells at various depths as follows: Wahpeton, 470 feet; Moorhead, Minnesota, across the river from Fargo, 365 feet; well 7 miles north of Moorhead, 255 feet; Casselton, 20 miles west of Fargo, 455 feet; Grand Forks, 385 feet; East Grand Forks, Minnesota, 325 feet; University, two miles west of Grand Forks, 425 feet; and Grafton, 40 miles north, 903 feet. The well at Rosenfeld, Manitoba, 14 miles north of the international boundary and 11 miles west of the Red River, reached the granite (or gneiss) at 1,035 feet.[1] In the Soldiers' Home well at Lisbon, a few miles west of the Red River Valley on the Cheyenne River, the granite was struck at 785 feet. The Moorhead well, which was drilled by the city in search of water and gas, is notable on account of the distance it went in the granite, the record being as follows: 220 feet of alluvial and lacustrine silt, 145 feet of bluish and greenish shales, with beds of sand, probably Benton, and 1,385 feet of granite and gneiss, thus reaching a depth of 1,750 feet.[2]

THE PALEOZOIC SYSTEMS

During at least a portion of this era the Paleozoic sea appears to have covered North Dakota, and in its waters were deposited the limestones, shales, and sandstones of the Cambrian, Silurian, and Devonian. Two or more of these systems outcrop not far to the north in Manitoba, to the east in Minnesota, and to the south

[1] G. M. Dawson, "On Certain Borings in Manitoba and the Northwest Territory," *Trans. Royal Soc. Canada*, IV, sec. 4 (1886), 85–91.

[2] Warren Upham, *U.S. Geol. Survey, Mono. No. 25*, 1896, p. 556.

in the Black Hills, but they are in this state deeply buried beneath more recent formations. The Grafton well passed through, beneath 298 feet of drift and Lake Agassiz silt, 605 feet of Paleozoic strata, including 288 feet of shale and sandstone, which has been referred to the Cambrian, and 317 feet of limestone, sandstone, and shale, which are believed to belong to the Ordovician.[1] In the deep well at Grand Forks, 40 miles south of Grafton, only one foot of limestone was found just above the granite, showing a rapid thinning of the formations in this direction, due either to inequality of deposition or to erosion. The Ordovician appears to thicken rapidly toward the north, for while at Grafton, as stated above, it is 317 feet thick, 60 miles north at Rosenfeld, Manitoba, it has increased to 700 feet, and is overlain by 192 feet of Silurian strata.[2] On the other hand, these formations thin out toward the west, and at Morden, 27 miles from Rosenfeld and 15 miles north of the international boundary, the Ordovician and Silurian are absent, as shown from the well record. The Dakota sandstone at Morden rests directly on the Devonian beds. In the Morden well, at a depth of 412 feet, 188 feet of Devonian red and gray shales and a thin layer of porous limestone were penetrated, and strata of this age cover a narrow strip of territory lying just west of the Silurian in Manitoba. It is not unlikely that these Devonian and Silurian strata extend south some distance into North Dakota. In the deep well at the Jamestown asylum 19 feet of limestone was penetrated at the bottom of the wells, at a depth of 1,505 feet. The well at LaMoure, about 40 miles southeast of Jamestown, struck a compact gray crystalline limestone with a pinkish tinge at 1,300 feet, and went 28 feet in this rock, stopping at a depth of 1,328 feet. The age of the limestone struck in these two wells is not known, though it is probably to be referred to the early Paleozoic. During the later Paleozoic the region does not appear to have been an area of deposition and probably remained above the sea also throughout a large part of the Mesozoic, since rocks belonging to the Triassic, Jurassic, and Lower Cretaceous or Comanchean are, so far as known, wanting in the state.

[1] *Ibid.*, p. 77. [2] G. M. Dawson, *op. cit.*

THE CRETACEOUS SYSTEM

Dakota sandstone.—The oldest Cretaceous formation in North Dakota is the Dakota sandstone which is reached in many wells but does not appear at the surface anywhere in the state. In the southeastern counties, as well as in South Dakota and elsewhere, the sandstone is the chief source of artesian water. It is a non-marine formation and was deposited either in a large lake or was spread by rivers over their broad flood plains. The Dakota sandstone underlies the entire state, except a considerable portion of the Red River Valley, where it has been removed by erosion (Fig. 1).

A rather fine-grained white sandstone, which is doubtless the Dakota, is found in a number of wells in the Red River Valley at depths ranging from 250 to 400 feet, and in several wells the sandstone was penetrated 100 feet. In southeastern North Dakota outside the valley, the Dakota sandstone is encountered at depths varying from about 500 feet near the western edge of the Red River Valley to 1,800 feet and over not far west of the James River and near the edge of the Missouri Plateau. The increasing depth of the formation is due both to the westward dip of the Dakota and the rise of the land surface in that direction. The depth of the sandstone at Enderlin is 640 feet; Valley City, about 800 feet; Oakes, 880 feet; Ellendale, 1,035 feet; and Jamestown, 1,450 feet. The deep well at Devils Lake, in the northeastern part of the state, struck the sandstone at 1,431 feet, while at Leeds, 30 miles northwest of Devils Lake, it lies at a depth of 2,110 feet. The Harvey well, near the center of the state, reached the Dakota at 2,235 feet, and a deep boring a few miles from Westhope, Bottineau County, entered the sandstone at about 2,100 feet. Though the well at Mandan reached a depth of 2,000 feet it failed to strike the Dakota, probably by several hundred feet.

As disclosed by the wells which penetrate it, the Dakota formation is a soft white or gray sandstone in beds 10 to 50 feet thick, separated by shale. In the regions where it occurs at the surface the sandstone has yielded an abundance of fossil leaves, the Dakota flora including no less than 450 species of trees and other plants.

GENERALIZED GEOLOGICAL SECTION OF NORTH DAKOTA

SYSTEM	SERIES	FORMATION NAME	COLUMNAR SECTION	THICKNESS IN FEET	CHARACTER OF ROCKS
QUATERNARY		LAKE SILT		0-30	Finely laminated sandy clay.
		Unconformity			
QUATERNARY		GLACIAL DRIFT		0-400	Boulder clay, sand, gravel & boulders.
		Unconformity			
TERTIARY	OLIGOCENE	WHITE RIVER FORMATION		40-400	Coarse sandstone containing pebbles, calcareous clay and fresh-water limestone.
		Unconformity			
TERTIARY	EOCENE	FORTUNION FORMATION		1000-1300	Yellow and ash-gray shale, sandstone, and clay, with numerous beds of lignite.
TERTIARY?		LANCE FORMATION		700-900	Cannonball marine member: Dark sandy shale, and shaly sandstone. Yellow sandstone, containing marine shells 0-300 feet. Ludlow lignitic member: Light sandy shale, calcareous sandstone and lignite. 0-350 feet. Dark-colored shale, yellow sandstone and thin lignite beds. 400-525 feet.
		Unconformity			
CRETACEOUS	MONTANA GROUP	FOX HILLS FORMATION		150	Yellow sandstone, with numerous concretions and marine shells.
CRETACEOUS	MONTANA GROUP	PIERRE SHALE		1100	Blue shale containing marine shells.
CRETACEOUS	COLORADO GROUP	NIOBRARA FORMATION		400	Chalky limestone and calcareous shale.
CRETACEOUS	COLORADO GROUP	BENTON SHALE		500	Dark-colored marine shale.
CRETACEOUS		DAKOTA SANDSTONE		300	Sandstone containing many plant remains.

FIG. 1

The thickness of the sandstone varies widely at different points but is commonly 200 to 300 feet. In the asylum well at Jamestown it is 200 feet thick, and at Valley City 300 feet of Dakota sandstone were penetrated, while at Aberdeen, South Dakota, the same thickness was encountered. In the eastern part of the state the Dakota sandstone has a westward dip of about 8 feet per mile.

After the deposition of the Dakota sandstone, marine conditions were brought about through the submergence of a large part of North America. The Gulf of Mexico invaded the continent, and finally stretched north to the Arctic Ocean. All of North Dakota was covered by the waters of this great inland sea, which extended east as far as central Minnesota. In it were deposited the muds, clays, calcareous shales, and sands which form the Benton, Niobrara, Pierre, and Fox Hills formations.

Benton shale.—The oldest formation which outcrops anywhere in North Dakota is the Benton shale (Fig. 2). It is exposed only in the deep valley of the Pembina River, in the northeastern corner of the state, where the shale outcrops at intervals for a distance of 6 or 7 miles, and rises 150 feet above the river. It is also found in many of the deep wells in different parts of the state. The Benton is a dark gray, almost black, fissile shale, containing a considerable amount of carbonaceous material. Small ferruginous concretions are abundant, and pyrite and gypsum are found in small quantity. The shale weathers to a very plastic clay and has been used in the manufacture of brick. One very marked difference between the Benton and the overlying Niobrara is its low lime content, from 1 to 2 per cent, while the Niobrara contains from 30 to 80 per cent of lime carbonate and generally carries over 50 per cent.

The thickness of the Benton shale in North Dakota is not definitely known, since in wells it is seldom distinguished from the overlying Cretaceous shales. In the Morden, Manitoba, well the thickness of the Benton is given as 105 feet, and the well at Deloraine, just north of the Turtle Mountains in the same province, showed a thickness of 205 feet, but the well did not reach the underlying Dakota sandstone, so that this does not represent the entire thickness of the formation.[1] In North Dakota it probably ranges

[1] J. B. Tyrrell, *Trans. Royal Soc. Canada*, VIII, sec. 4 (1891), 93, 98.

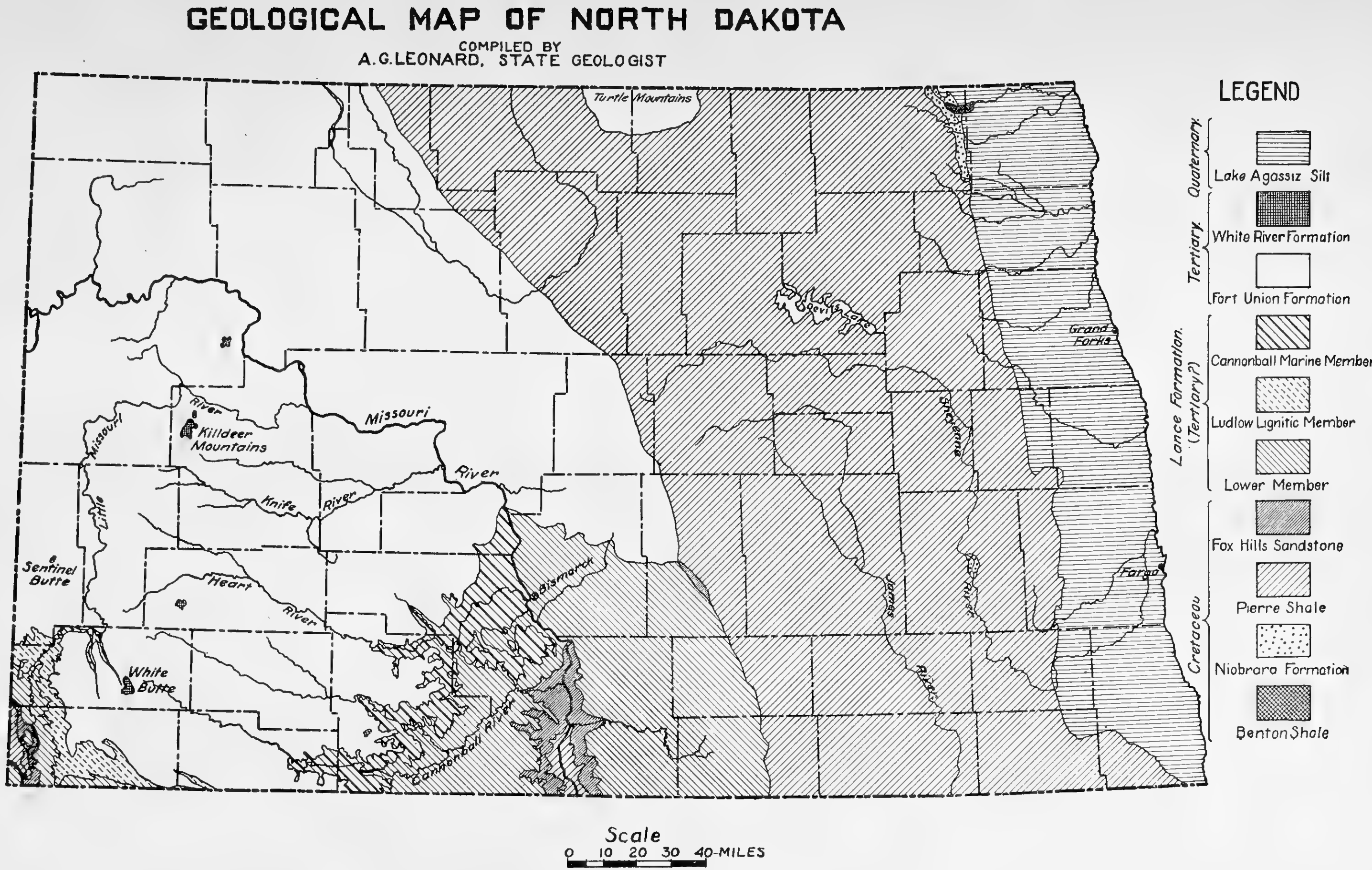
GEOLOGICAL MAP OF NORTH DAKOTA
COMPILED BY
A.G.LEONARD, STATE GEOLOGIST
LEGEND
Quaternary
Lake Agassiz Silt
Tertiary
White River Formation
Fort Union Formation
Lance Formation. (Tertiary?)
Cannonball Marine Member
Ludlow Lignitic Member
Lower Member
Cretaceou
Fox Hills Sandstone
Pierre Shale
Niobrara Formation
Benton Shale
Turtle Mountains
Devils Lake
Grand Forks
Fargo
Sheyenne
River
James
River
Missouri
River
Killdeer Mountains
Knife
River
Heart
River
Little
Missouri
Sentinel Butte
White Butte
Bismarck
Cannonball River
Scale
0 10 20 30 40-MILES

FIG. 2

from 200 to 600 feet or more. In northeastern South Dakota wells have encountered 400 to 480 feet of Benton.

While the Cretaceous formations have been largely removed by erosion from the Red River Valley, a dark-colored shale overlying a soft sandstone has been encountered in a number of wells in different parts of the valley, and it seems not improbable that this is the Benton shale. In that case this shale underlies the drift over a portion of the valley.

Niobrara formation.—Overlying the Benton, the upper member of the Colorado group is present in the wooded escarpment known as the Pembina Mountains, which border the Red River Valley on the west, in eastern Cavalier County. This escarpment extends far to the north in Canada, and the formation appears in the Tiger Hills, Riding and Duck mountains, and the Pasquia Hills. In North Dakota the Niobrara occupies a narrow belt extending 30 miles south of the international boundary, the outcrops being found along the Pembina, Tongue, north fork of Park River, and tributaries of these streams, which have cut deep valleys in the escarpment and exposed the Niobrara beneath the Pierre shale. A highly calcareous shale exposed in the valley of the Cheyenne River at Valley City is also probably to be referred to the Niobrara. It contains 45 per cent of carbonate of lime, and lies just below the black and white bands forming the base of the Pierre, as described on a later page.

The Niobrara is a light to dark gray, moderately hard calcareous shale. It contains numerous small white specks of lime which give it a finely mottled or speckled appearance, plainly seen on fresh fractures. Where the rock has been weathered it becomes almost white and has a chalky appearance; in fact, in many localities outside the state the formation is a nearly pure chalk. Its lime content, which is the most marked characteristic of the Niobrara, is due almost entirely to the presence of minute Foraminifera which are readily seen under the microscope. The most abundant forms are the two species so common in chalk, *Globigerina cretacea* and *Textularia globulosa*. The fact that these Foraminifera are mingled with clay is evidence that the sea in which they lived was not clear, but contained more or less fine sediment and the shells settled to

the bottom along with the clay to form the calcareous shale or chalky marl of this Cretaceous deposit.

The percentage of lime carbonate in the different layers varies widely, ranging from 30 per cent and less to 75 per cent. Many of the beds are suitable for making natural hydraulic cement and are used for this purpose, while certain layers have almost or quite the composition of a natural Portland cement rock.

Wherever the Niobrara formation is exposed in the Pembina Mountains it maintains a fairly uniform character throughout its thickness of 150 feet and more. By far the greater portion of the aggregate thickness is formed of a rather dark bluish-gray speckled rock, which commonly varies in lime carbonate content from 55 to 65 per cent in passing from one layer to another. Generally the more speckled the rock appears the higher it is in lime. Between these thicker beds high in lime carbonate are others much thinner, varying from a few inches to a foot in thickness, which are much lower in lime.

Where exposed in northeastern North Dakota the Niobrara strata have yielded a number of vertebrate and invertebrate fossils. Among the latter are *Inoceramus labiatus*, specimens of *Ostrea* and *Avicula*, besides the microscopic forms previously mentioned. The large diving bird, *Hesperornis*, several species of fishes, *Plesiosaurus*, and the vertebrae of a crocodile have also been found.

The maximum thickness of the Niobrara in the Pembina Mountains is 165 feet. At Morden, Manitoba, the formation is 160 feet, and farther north it averages from 150 to 200 feet, but seems to thicken toward the west, for the well at Deloraine, a few miles north of the Turtle Mountains, shows a thickness for the Niobrara of 545 feet. The formation probably has a thickness of at least 400 feet in southern and central North Dakota, since at Valley City the combined thickness of the Benton and Niobrara is about 900 feet. The artesian wells at this place reach the Dakota sandstone at a depth of approximately 800 feet below the bottom of the Cheyenne Valley, and the calcareous shale, which outcrops in the sides of the valley and is believed to be Niobrara, rises about 80 feet above the well curbs. The thickness of the beds between the top of the Dakota sandstone and the base of the Pierre is thus

about 900 feet at this point, and the Niobrara probably includes 300 to 400 feet of the section.

Pierre shale.—The Pierre shale occupies most of the eastern half of North Dakota west of the Red River Valley. It also outcrops along the valley of the Missouri River for a distance of over 20 miles north of the South Dakota line, and is brought to the surface in the southwestern corner of the state by the Cedar Creek anticline, which lies mostly in Montana. Throughout the large eastern area it is covered by glacial drift, except where the streams have cut through this mantle and exposed the shale beneath. The Pierre outcrops in many places along the James and Cheyenne rivers and is finely exposed along the South Branch of Park River and other tributaries of the Red River in the region of the Pembina Mountains. The escarpment of the Pembina Mountains is composed largely of this shale, which is well shown in the numerous ravines and gorges, while in places the underlying Niobrara is also seen. The base of the Pierre as found in this region is composed of black, jointed, carbonaceous shales which contain many thin layers of yellow or white non-plastic clay, which has much of the consistency of cheese. The black and yellow strata present a striking appearance and seem to be characteristic of the base of the Pierre over extensive areas. They appear at frequent intervals for a distance of 30 miles along the Pembina Mountain escarpment and extend at least 250 miles northwestward in Canada, where they have been noted in the Riding and Duck mountains. They are also found 130 miles south of the Pembina Mountains at Valley City. The yellow or white clay seams vary in thickness from 1 to 6 inches, and the interstratified black layers from 8 to 14 inches. The uniformity and extent of some of the yellow seams are remarkable because they have been traced continuously for a distance of 35 miles, and a single clay seam 2 inches thick for 25 miles.

The typical Pierre overlying these basal beds is a bluish-gray to dark gray jointed shale of remarkably uniform character, which often weathers into small flaky fragments. The rock commonly shows yellow spots or stains of iron oxide. Erosion has removed the upper part of the formation over most of the large eastern Pierre area, but the topmost beds, where exposed in the southwest

corner of the state, contain numerous calcareous concretions varying in size from a few inches to 6 and 8 feet in diameter. Many of these are rich in marine shells, including the following: *Scaphites nodosus* Owen vars. *brevis* and *plenus*, *Anisomyon patelliformis* M. and H., *Inoceramus cripsi* var. *barabina* Morton, *Avicula linguæformis* E. and S., *Ostrea pellucida* M. and H., *Chlamys nebrascensis* M. and H., *Yoldia evansi* M. and H., *Nucula cancellata* M. and H., *Lucina occidentalis* Morton, *Protocardia subquadrata* E. and S., *Callista deweyi* M. and H., and *Nautilus dekayi* Morton.[1]

Below the upper beds of the Pierre, fossils are found only sparingly, those which do occur being *Baculites ovatus* Say, *Scaphites nodosns* Owen, and *Inoceramus sagensis* Owen.

The position of the western boundary of the large Pierre area is known only approximately, since the region is heavily drift-covered and there are practically no outcrops. Not far west of the boundary as represented on the map (p. 7) Fort Union lignite beds are known to occur, so that the Pierre shale is believed to disappear beneath the overlying Fort Union about as shown. It will be noted that no areas of Fox Hills or Lance are represented on the map along most of the margin of the Pierre shale. These formations are not known to underlie the drift farther north than indicated on the map, and in the absence of information regarding their presence in the central and northern parts of the state they are not mapped in that region. If they are actually absent from that area it would of course mean an unconformity between the Pierre and the overlying Fort Union.

The Pierre is the thickest Cretaceous formation in North Dakota, reaching 1,000 to 1,100 feet or over. It is not likely that its entire thickness is represented throughout most of the large eastern area, since the formation had undergone great erosion before being covered by the glacial drift and hundreds of feet were doubtless removed in many places. The aggregate thickness of the Benton, Niobrara, and Pierre is considerably greater in North Dakota than in northeastern South Dakota. In the latter region the aggregate thickness of these formations ranges from 700 to 900 feet, but they become thicker to the north and northwest, where

[1] Identified by Dr. T. W. Stanton.

they reach from 1,300 to about 2,235 feet. At Jamestown they are 1,330 feet thick, at Devils Lake, 1,403 feet, Leeds, over 2,000 feet, and at Harvey they are not far from 2,235 feet thick. The deepest well in the state, at Max, 30 miles south of Minot, has a depth of about 2,400 feet, but it passed through drift, some Fort Union, and probably the Lance before entering the Cretaceous shales, and it did not reach the Dakota sandstone. The Deloraine well not far north of the international boundary went through 1,800 feet of shales, including some Fort Union strata, without reaching the Dakota.

Fox Hills sandstone.—This upper member of the Montana group is known to outcrop in three separate areas in North Dakota. The largest of these is along the Missouri River, where the formation is exposed for over 40 miles north of the South Dakota line and extending 5 to 10 miles on either side of the river. A narrow belt of Fox Hills sandstone surrounds the Pierre area in the southwestern corner of the state, and there is a small outcrop near the center of the state.[1]

The Fox Hills is particularly well shown along the Cannonball River for a distance of over 12 miles above its mouth, where the sandstone forms vertical cliffs rising from 80 to 90 feet above the river and is overlain by banded shale. The sandy portion of the formation is a yellow, rusty brown or gray, rather soft sandstone. Cross-bedding is very common, and the formation contains great numbers of large and small ferruginous sandstone concretions and indurated masses and layers, these also exhibiting cross-bedding. The concretions are apparently due to the segregation of the iron in certain portions of the rock, cementing the sand into firm, hard masses, considerably harder than the sandstone in which they are imbedded. These concretionary masses vary in size from an inch and less to 6 and 8 feet. Small, irregular, twisted or stemlike forms are abundant in places. Some portions of the rock are so completely filled with these rusty brown concretions that they constitute the main bulk of the formation, and the gray, loosely cemented sandstone forms a kind of matrix, in which the harder concretions are imbedded. In the process of weathering these

[1] Described by Dr. T. W. Stanton in a letter to the writer.

more resistant masses project beyond the softer rock, and at the base of slopes and scattered over the surface they are exceedingly abundant. Many of the concretions are spherical in shape and of good size, and it is these which have given the name to the Cannonball River, since they occur abundantly along that stream.

In the southwestern area in Bowman County the Fox Hills is composed of 60 feet of massive gray sandstone, which weathers to a yellow color, and below this is 25 feet of sandy clay formed of light and dark laminae.

Marine fossils are quite abundant in the Fox Hills sandstone, and the following are among those found in the Missouri River area and identified by Dr. T. W. Stanton: *Tancredia americana* M. and H., *Callista deweyi* M. and H., *Ostrea pellucida* M. and H., *Avicula linguiformis* E. and S., *Avicula nebrascana* E. and S., *Protocardia subquadrata* E. and S., *Tillina scitula* M. and H., *Mactra warrenana* M. and H., *Scaphitis cheyennensis* (Owen) and *Chemnitzia cerithiformis* M. and H.

The Fox Hills in North Dakota ranges in thickness from 85 to about 200 feet, with an average of about 150 feet.

CRETACEOUS OR TERTIARY SYSTEM

Lance formation.—As shown on the geologic map (p. 7) this formation occupies a considerable area on either side of the Missouri River in south-central North Dakota, and a smaller area in the extreme southwestern corner of the state. The beds are well exposed in the bluffs of the Missouri, particularly on the west side of the river 15 to 20 miles below Bismarck, and in many places along the Cannonball and Heart rivers. The bluffs and badlands of the Little Missouri in Slope and Bowman counties also afford many excellent outcrops.

As shown by Lloyd,[1] the Lance formation in south-central North Dakota consists of a lower portion of shale and sandstone beds of continental origin, and an upper member of sandstone and shale of marine origin which is known as the Cannonball marine member. Farther west in Slope and Bowman counties the upper member of

[1] E. R. Lloyd, "The Cannonball River Lignite Field, North Dakota," *U.S. Geol. Survey, Bull. No. 541*, 1914, p. 249.

the Lance is non-marine and lignite-bearing and has been named the Ludlow lignitic member.[1] The Cannonball marine and Ludlow lignitic members occupy similar stratigraphic positions and are believed to be contemporaneous in age.

The lower part of the Lance is best exposed in the badlands bordering the Little Missouri River in Bowman and Slope counties, where it is composed of shales alternating with soft gray or yellow sandstones, the beds having a notably dark and somber aspect. The prevailing colors are dark gray, but beds of brown carbonaceous shale are common and conspicuous. Much dark brown ferruginous material is present, occurring both in thin seams and concretions, the latter being most numerous at certain horizons, and fragments of this cover the slopes in many places. Another characteristic is the great number of sandstone concretions, some small and others 8 to 10 feet in diameter. Only occasional thin seams of lignite are found in the lower part of the Lance.

The Ludlow lignitic member in North Dakota is similar lithologically to the lower part of the Lance except that numerous beds of lignite are present. In western Slope County it contains at least 5 lignite beds which are from 4 to 30 feet in thickness.

The flora of both the lower part of the Lance and the Ludlow lignitic member is similar to that of the overlying Fort Union, the great majority of the species being common to both formations, according to Knowlton.[2] The Lance thus has a Fort Union flora. The characteristic vertebrate fossils of the Lance are the three-horned dinosaur *Triceratops*. *Trachodon* bones are also present in these beds.

The Cannonball marine member has been mapped only west of the Missouri River, and while, in the absence of outcrops, it is not represented on the geologic map as occurring east of the river, it seems not unlikely that it may be present beneath the drift, and that a portion of the area mapped as the lower member of the Lance is occupied by the Cannonball marine member. On account of

[1] E. R. Lloyd and C. J. Hares, "The Cannonball Marine Member of the Lance Formation of North and South Dakota and Its Bearing on the Lance-Laramie Problem, *Jour. Geol.*, XXIII (1915), 523–47.

[2] *Proc. Wash. Acad. Sci.*, XI (1909), 218–24.

the heavy covering of drift the eastern boundary of the area is probably only approximately correct.

Not only is the Cannonball marine member well exposed along the river from which it is named, but it is also well shown in many outcrops along the Heart River in the vicinity of Mandan and in the bluff of the Missouri near Bismarck. It is composed of dark gray to black shale, arenaceous in part, with a subordinate amount of gray and yellow sandstone. Some thin beds of limestone are also present.

After the deposition of the Fox Hills sandstones the Cretaceous sea withdrew from the region for a time and the beds constituting the lower part of the Lance were formed. These and the Ludlow lignitic member of the western area are of continental origin and were probably formed in part by rivers, though much of the formation may be of lacustrine origin. As the lakes were filled with sediment, they were converted into swamps in which trees and other vegetation grew and accumulated year after year to form the beds of lignite which are characteristic of the upper non-marine portion of the Lance. But while this Ludlow lignitic member was being deposited to the west the sea again entered the region, perhaps from the east, and in its waters were formed the Cannonball marine member, with its abundant fauna of marine shells, which Dr. Stanton characterizes as a modified Fox Hills fauna.[1] That this sea may have extended westward almost to the Montana line is suggested by the occurrence in the Little Missouri badlands of western Slope County of a bed containing *Ostrea glabra* and *Ostrea subtrigonalis*. Since these oysters are brackish-water forms the open sea was probably not far distant, and the shale bed containing them appears to be the westward extension of the Cannonball marine member. The zone in which the shells are found lies 120 feet below the top of the Ludlow lignitic member. Following the deposition of the Cannonball marine member the sea withdrew from the region never to return again.

The thickness of the Lance formation along the Little Missouri is about 820 feet, the upper 300 feet representing the Ludlow lignitic member. In the Cannonball River region the Lance is about 700 feet thick.

[1] E. R. Lloyd and C. J. Hares, *op. cit.*, p. 537.

The relation of the Lance formation to the underlying Fox Hills is of importance as bearing on the age of the former. In many localities in Wyoming, Montana, and South Dakota, where the contact has been observed, the Lance rests unconformably on the Fox Hills. On Little Beaver Creek in northwestern Bowman County the Fox Hills sandstone had undergone erosion before the deposition of the Lance beds, and although it has been questioned whether this erosion represents a long time interval, the relationship elsewhere suggests the probability that the unconformity here may represent a considerable interval.

Lying as it does on the border line between the Cretaceous and Tertiary, with its Fort Union (Tertiary) flora and its vertebrate fauna of Mesozoic types, the age of the Lance formation is still undetermined. Some would place it in the Tertiary while others would include it with the Cretaceous on account of its dinosaurs and other Mesozoic forms.

TERTIARY SYSTEM

Fort Union formation.—Overlying the Lance and resting in some places on the Cannonball marine member, in others on the Ludlow lignitic member, is the Fort Union formation. Deposition went on without interruption from the beginning of Lance time to the close of Fort Union time, during which over 1,800 feet of sediments accumulated, all of continental origin except those of the Cannonball marine member.

The Fort Union formation, which covers the greater part of western North Dakota, contains most of the lignite deposits of the state, the lignite beds of the Lance being relatively unimportant. Outcrops are abundant in the Little Missouri badlands, as well as along the Missouri and other streams of the region, and these extensive outcrops afford exceptional opportunity for the study of the formation. The Fort Union is remarkably uniform in color, composition, and general appearance over many thousands of square miles. It is composed of shales alternating with soft sandstone and contains numerous beds of lignite. The prevailing colors are light ash gray and yellow, but some layers are nearly white.

One of the most conspicuous features of the Fort Union is the vast quantity of baked and fused rock, or clinker, produced by the heat of the burning lignite beds. The overlying shales and sandstones have been burned to a red or pink color and in places completely fused to slaglike masses. This clinker caps many of the ridges and buttes of the region, having protected them from erosion by its superior hardness. The beds of clinker vary in thickness from 5 or 6 to 40 feet and over, the thicker masses probably having been produced by the burning of several lignite beds and the baking of the intervening shales, all now forming a single bed.

The Fort Union everywhere contains numerous beds of lignite. These vary in thickness from an inch and less to 35 feet, beds 6, 8, and 10 feet thick being common. Many of the lignite beds cover large areas. One with a thickness of from 5 to 16 feet has a known extent of 20 miles in one direction and 25 in another, thus covering an area of at least 500 square miles. Another is known from its outcrops to have an area of over 900 square miles, and its probable extent is from 1,000 to 1,500 square miles. This bed ranges in thickness from 9 to 15 feet and over. The lignite is found from top to bottom of the Fort Union, and since it is present also in the upper part of the Lance formation it has a vertical range of from 1,200 to 1,300 feet.

The Fort Union, which is Lowest Eocene, or Paleocene, in age, contains an abundant flora, about 300 species of plants having been described from this formation. It has a fauna comprising both fresh-water shells and vertebrates. Among the former are *Unio priscus* M. and H., *Viviparus trochiformis* M. and H., *Viviparus leai* M. and H., *Viviparus retusus* M. and H., *Campeloma multilineata* M. and H., *Campeloma producta* White, and *Corbula mactriformis* M. and H. Among the vertebrate remains are fishes, turtles, the aquatic reptile *Champsosaurus laramiensis*, and mammalian teeth.

A large part of the Fort Union formation has been removed by erosion and only in the higher buttes and divides of western North Dakota has the upper part been preserved. In Billings and Golden Valley counties it has a thickness of 1,000 feet, while farther north, in McKenzie County, the formation reaches 1,300 feet in thickness.

The shales and sandstones of the Fort Union appear to be very largely of lacustrine origin. The channel sandstones and the conglomerates which are present in places at the base of the formation were probably deposited by rivers, as were some of the shales and sandstones above, but the greater part of the sediments appears to have been laid down in lakes, many of them of large size and occupying parts of North Dakota, Montana, South Dakota, Wyoming, and a considerable area in Canada. This region is believed to have been a great flat plain occupied by numerous lakes, and over this plain large sluggish rivers took their meandering course. Thus deposits made on the flood plains of rivers, and wind deposits, are doubtless represented in the Fort Union, along with lacustrine deposits, which make up the bulk of the formation.

Various features characteristic of fluviatile deposits, such as local unconformities and filled channels, are, so far as known, not found in the Fort Union except at the base of the formation, and cross-bedding is of rare occurrence in the sandstones. Were the shales and sandstones of the Fort Union formed chiefly through deposition by rivers the foregoing features should be present, and the fact that except for a little cross-bedding they are not found above the base suggests that the deposits are lacustrine in large part.

The numerous lignite beds of the Fort Union are evidence that the region was occupied again and again by swamps, many covering hundreds and even thousands of square miles. These were probably formed by the partial filling of the lakes with sediment brought in by rivers, thus converting them repeatedly into swamps. The coal-forming vegetation growing in these swamps consisted, as determined by Thiessen,[1] very largely of coniferous trees, including varieties related to the Sequoia, cypress, juniper, and arbor vitae, together with some firs and spruces. The woody material of these trees, including trunks, stems, and branches, comprises roughly 75 to 85 per cent of the whole mass of the lignite. That the vegetation accumulated in some of these swamps for thousands and tens of thousands of years is indicated by the fact that several

[1] David White and Reinhardt Thiessen, "The Origin of Coal," *Bureau of Mines, Bull. No. 38*, 1913, p. 222.

of the lignite beds have a thickness of 20 feet and one of 35 feet. That the coal swamps recurred repeatedly in many parts of the region is proved by the presence in some vertical sections of as many as 15 or 20 lignite beds, the majority of them, it is true, of no great thickness. Among the lakes and swamps there grew many varieties of trees, including, according to Knowlton,[1] the poplar, oak, walnut, fig, elm, maple, birch, alder, dogwood, hickory, box elder, buckthorn, viburnum, witch-hazel, horse chestnut, and bittersweet. Interspersed with these were scattered conifers and ginkgos. Thus during Fort Union time North Dakota and adjoining areas were covered with dense forests. Osborn thus describes the region as it was at this period: "Vast stretches of subtropical and more hardy trees were interspersed with swamps where the vegetation was rank and accumulated rapidly enough to form great beds of lignite. Here were bogs in which bog iron was formed. Amid the glades of these forests there wandered swamp turtles, alligators, and large lizards of the characteristic genus *Champsosaurus*."[2]

White River formation.—The deposition of the Fort Union sediments was followed by a long erosion interval during which hundreds of feet of strata were removed. Erosion was going on during most of the Eocene period, and a well-marked unconformity therefore separates the Fort Union from the overlying White River formation of the Oligocene.

The White River beds occupy a number of small and widely scattered areas west of the Missouri River. It is necessary to exaggerate the size of these areas in order to represent them on the geologic map (p. 7). The formation is especially well exposed in White Butte, in Slope County, where it covers an area of 8 to 10 square miles, forming the highest portion of the divide at the headwaters of the north fork of the Cannonball River and Sand and Deep creeks. It is here composed of white clays at the bottom, on which rests a coarse sandstone filled in places with large pebbles; this is overlain by about 100 feet of calcareous clays, which in turn are overlain by more than 100 feet of fine-grained greenish sandstone. These deposits represent all three members of the White

[1] F. H. Knowlton, *U.S. Geol. Survey, Bull. No. 611*, 1915, p. 59.

[2] H. F. Osborn, *The Age of the Mammals*, p. 100.

River formation, the lower or Titanotherium beds, the middle or Oreodon beds, and the upper or Protoceras beds.

It is probably this area, in what was then Dakota Territory, which was visited by E. D. Cope in 1883, and from it he collected twenty species of vertebrates, including *Trionyx, Galecynus gregarious, Aceratherium, Elotherium ramosum, Oreodon, and Leptomeryx.*

The beds of the White Butte locality have been described in considerable detail by Earl Douglass,[1] and in the middle member, or Oreodon beds, he found the following vertebrate fossils: *Ictops, Ischyromys, Palaeolagus, Merycoidodon culbertsoni, Leptomeryx evansi, Mesohippus, Hyracodon, Gymnoptychus, Eumys,* and *Aceratherium.* Another White River area was discovered by Douglass about 30 miles northeast of White Butte, in western Stark County. All three members of the White River formation are here present and contain mammalian bones.

The 40 feet of calcareous clay and compact, siliceous, thin-bedded limestone occupying a few acres on top of Sentinel Butte, in Golden Valley County, is referred to the White River formation. Seventy miles east of White Butte, in Grant County, the White River formation occurs on the tops of three high buttes. The deposits are briefly described by E. R. Lloyd[2] as consisting of about 50 feet of calcareous sandstone overlying a marly limestone, both being referred to this formation "on faunal and lithologic evidence."

Far to the north of the above-mentioned areas, in the Killdeer Mountains of northwestern Dunn County, there are 400 feet of strata which are so wholly unlike the underlying Fort Union, on which they rest unconformably, that they have been referred to the White River formation. This area has recently been described by T. T. Quirke.[3] The deposits here consist of green or pink non-plastic clays, green friable calcareous sandstones, limestones, and chalklike arenaceous marl. The rocks are similar in character to those of the White River formation found elsewhere in the region, and they undoubtedly belong to that formation.

[1] *Annals of the Carnegie Museum*, V, Nos. 2 and 3 (1909), 281–88.

[2] E. R. Lloyd, "The Cannonball River Lignite Field, North Dakota," *U.S. Geol. Survey, Bull. No. 541*, 1914, p. 251.

[3] T. T. Quirke, "The Geology of the Killdeer Mountains, North Dakota," *Jour. Geol.*, XXVI (1918), 255–71.

About 25 miles north and east of the Killdeer Mountains, in eastern McKenzie County, many of the high buttes are capped with 200 feet of strata resembling those in the Killdeer Mountains. It is believed that the greenish sandstones and greenish clays of these buttes are likewise to be referred to the White River formation.

The strata in all these localities are clearly only remnants of much larger areas which have suffered extensive erosion and only relatively small patches of the White River formation have been left. It is not unlikely that several of those nearest together may formerly have been connected.

The beds of this formation are in part lake deposits and in part river deposits. Those of Sentinel Butte, the easternmost areas in Grant County, and most of the beds of the Killdeer Mountains are doubtless of lacustrine origin, while portions of the deposits of White Butte and the next area to the north are likewise lake deposits. The coarse pebbly sandstones and perhaps other strata were deposited by rivers.

While western North Dakota was an area of deposition in Lowest Eocene or Paleocene time and also during the early part of the Oligocene epoch, nevertheless during most of the Tertiary period the region was undergoing erosion. This resulted in the removal of many hundreds of feet of strata over most of the state, and in places the aggregate thickness of the Cretaceous and Tertiary deposits thus carried away by streams amounted to 1,000 feet and over. The outlier known as the Turtle Mountains, the Fort Union strata of which were once continuous with those of the Missouri Plateau, was during this time separated from the plateau by the denudation of the intervening area. The broad depression of the Red River Valley was cut to a depth of 800 to 900 feet in the Cretaceous and older rocks of eastern North Dakota and Minnesota by a large northward-flowing river. The topographic features of the region west of the Missouri River, including the rolling uplands, the high ridges and divides, the numerous buttes, the escarpments, and badlands, were all formed in large measure by erosion during the Tertiary period, continued, of course, in the Pleistocene.

Since the Cretaceous and Tertiary strata were deposited they have undergone but little deformation, though the region has several times been elevated, in the aggregate to the extent of some

2,000 to 3,000 feet. Only locally has there been warping or folding of the strata, as in the Cedar Creek anticline, which extends from near Glendive, Montana, southeast into southwestern North Dakota.[1] This anticline was probably formed about the close of Fort Union time and prior to the deposition of the White River beds.

QUATERNARY SYSTEM

Pleistocene deposits.—The Cretaceous and Tertiary formations are largely buried beneath a mantle of Pleistocene deposits left by the ice sheets which once covered the region. These deposits conceal the bed rock except where they have been cut through by streams, thus exposing to view the underlying formations. With the exception of the Lake Agassiz silt of the Red River Valley the Pleistocene deposits are not shown on the geologica lmap (p. 7). but they cover the entire state, except the southwest corner. The preglacial surface on which they rest had undergone great erosion during the Tertiary period, as already stated, and was therefore doubtless quite uneven and rough and cut by many stream valleys. These surficial deposits rest on the Archean granite and Paleozoic rocks in the Red River Valley; farther west they rest on the Pierre and other Cretaceous formations, and in western North Dakota they directly overlie the Tertiary strata. They overlie the earlier formations without regard to altitude, the surface on which they rest ranging in elevation from 450 to 2,500 feet above sea-level.

Glacial drift.—The only portion of the state which was not buried beneath the Pleistocene ice sheets, and hence did not receive a deposit of drift, is the southwest corner. The drift extends from 40 to 60 miles west and south of the Missouri River, though it is here represented largely by gravel and bowlders, since the till is thin and in scattered patches.

There are at least two, and probably three, drift sheets in North Dakota, namely, Late Wisconsin, Early Wisconsin, and an older drift, which may be referred to provisionally as the Kansan, though it may prove to be younger. The Late Wisconsin drift covers

[1] A. G. Leonard, *U.S. Geol. Survey, Bull. No. 285*, 1906, p. 317; *No. 316*, 1907, pp. 195, 203; W. R. Calvert, *U.S. Geol. Survey, Bull. No. 471*, 1912, p. 201.

considerably over one-half the state, including the eastern and northwestern portions, and its western border is marked by the wide, massive Altamont moraine, which in places has a width of 20 miles and over. Outside of the Altamont moraine there is in northwestern North Dakota and perhaps elsewhere in the state a drift which is little older than that within the moraine, and is itself marked by occasional morainic patches. This young drift, which in Williams County extends 20 miles or more south of the Altamont moraine, is probably Early Wisconsin. Beyond the Early Wisconsin till and appearing at the surface for the most part west and south of the Missouri River, is a distinctly older drift whose age is not yet definitely determined, but which may be Kansan. This pre-Wisconsin drift has been described elsewhere[1] and need not be discussed more fully here. It forms well-developed moraines in northeastern Morton and northern McKenzie counties.

In marked contrast to the older drift the Wisconsin has suffered very little erosion, its surface is poorly drained, is characterized by almost countless lakes, ponds, swamps, and marshes, and by many rough, hilly, morainic belts. Twelve of these moraines, including the remarkably wide and massive Altamont moraine, have been mapped in eastern North Dakota[2] and adjoining regions.

The drift varies in thickness from a few feet to 300 and even 400 feet, though the latter thickness is probably exceptional. In the Red River Valley the till is commonly from 200 to 300 feet thick, and in other parts of the state covered by Wisconsin drift the thickness appears to be somewhat less, ranging usually from 150 to 250 feet. The pre-Wisconsin drift is much thinner, the maximum thickness so far noted being 100 feet. West of the Missouri River it is seldom as much as 8 or 10 feet and generally not over 2 or 3 feet or less.

Lake Agassiz silt.—In the Red River Valley the glacial drift is in most places covered by a fine silt which was deposited in Lake Agassiz toward the close of the Pleistocene. Associated with this

[1] A. G. Leonard, "The Pre-Wisconsin Drift of North Dakota," *Jour. Geol.*, XXIV (1916), 521–32.

[2] Warren Upham, "Glacial Lake Agassiz," *U.S. Geol. Survey, Mono. No. 25*, Plate XVII.

are alluvial deposits spread over the surface by the Red River and its tributaries. This fine, thinly laminated silt commonly has a thickness of 30 to 50 feet, though in places it is considerably less.

Where rivers entered the lake the sediment carried by them accumulated to form delta deposits. Three such deltas are found in North Dakota, the largest, formed by the Cheyenne River, covering an area of about 800 square miles. The sand of this delta has been heaped by the wind into dunes, and a large tract of the delta is covered by these sand hills.

Recent deposits: alluvium.—Alluvium is found along practically all the streams of the state, being deposited by the rivers over their valley bottoms in time of flood, and in some of the larger valleys it has accumulated to a considerable depth. It is composed of sand, clay, and gravel, the upper 2 or 3 feet being commonly clay. The belt of alluvium along the Missouri River averages 2 to 3 miles in width. As shown by borings, the silt deposited by this river reaches in places a thickness of nearly 100 feet. Some of it may have been deposited during the Pleistocene, but much of this alluvium of the Missouri and other rivers belongs to the Recent epoch.

Quaternary history.—In conclusion the course of events during the Quaternary period may be briefly described. At the close of the Tertiary the warmth of a temperate climate gave way to the rigors of an arctic cold. North Dakota was several times invaded by an ice sheet and many of the surface features as we find them today are the result of these invasions, particularly of the most recent one. The ice of the earlier invasion crossed the broad and deep valley of the Missouri and extended from 40 to 60 miles beyond that river. The deposits of this older glacier are in most places thin and appear to have undergone much erosion. This drift west of the Missouri may never have been very thick, except locally, where it forms moraines, and much of the finer material of the till has been swept away by the streams, leaving behind the gravel and bowlders.

This ice invasion produced important changes in the preglacial drainage of the region. The Missouri Valley and the lower valleys of the Yellowstone and Little Missouri rivers were blocked with

ice, so that all these streams were forced to seek new channels. Lakes were formed in the valleys of the Yellowstone and Little Missouri rivers, the water rising until it overflowed at its lowest point the divide between the latter and the Knife River. The combined waters of the three rivers flowed east and southeast to the mouth of the Cannonball, where they entered the Missouri Valley. The length of this Pleistocene valley from the head of the Knife to the mouth of the Cannonball is 155 miles. Upon the withdrawal of the ice sheet the Missouri and Yellowstone rivers returned to their former valleys, but the lower valley of the Little Missouri was permanently abandoned and that river took an easterly course from the point where its preglacial course was blocked by the front of the ice sheet.

After the first invasion the climate grew warmer and the glacier retreated northward, so that conditions were probably favorable for the return of animal and plant life. Upon the recurrence of the cold climate the ice sheet again advanced over the region and probably reached about to the Missouri River. Evidence that this second advance crossed the latter stream is lacking, and it is known to have stopped far short of the limits reached by the first invasion. Then after a relatively short interglacial interval, during which the glacier withdrew from the region, there was a third invasion of the ice sheet, coming as before from the center west of Hudson Bay. The limit reached by this Late Wisconsin ice sheet is marked by the Altamont moraine. This remarkably well-developed moraine forms a very rough belt of massive hills and ridges which extends without interruption for hundreds of miles. In places it is fully 20 miles wide and throughout much of its extent in North Dakota its width probably averages 12 to 15 miles. While forming the moraine the ice front doubtless fluctuated back and forth across the belt for a long period.

During its recession the ice sheet halted again and again and thus built a series of moraines. Some of these halts were brief and the resulting moraines poorly defined; others were of much longer duration, as shown by the great amount of material deposited and the large size of the hills and ridges.

Lake Agassiz: The early history of Lake Agassiz, according to Upham,[1] was intimately connected with the recession of the ice front, since when the glacier had retreated across the divide between the Minnesota and Red rivers the lake was formed by the ponding of the water at the south end of the Red River Valley. According to this view, Lake Agassiz began as a small body of water and expanded northward as the ice melted until its maximum was attained, its area at that time being about 110,000 square miles.

Recently W. A. Johnson, of the Canadian Geological Survey, has attributed a different life-history to Lake Agassiz.[2] He believes with Tyrrell that after the retreat of the Keewatin glacier northward into Manitoba there was comparatively free drainage in that direction, so that an earlier glacial marginal lake associated with a lobe of the Keewatin glacier was largely or wholly drained. Lake Agassiz proper did not come into existence until a later advance of the ice from the northeast was met by a slight advance of the Keewatin glacier, which resulted in the ponding of the northward drainage and the initial stage of the lake. The waters gradually rose and extended southward, filling the Red River Valley and overflowing to the south.

It will be noted that these two views differ radically, one holding that the lake began at the upper or south end of the valley and expanded northward with the retreat of the ice margin; the other, that the lake originated well to the north in Manitoba after much of the Red River Valley was already free of ice, and had first a rising stage as it increased in size and extended southward over the valley floor. But in either case Lake Agassiz owed its existence to the presence of the ice barrier to the north and northeast, higher land holding in its waters on the other sides of the basin.

This Pleistocene lake left its mark on the region in the form of beaches, deltas, and lacustrine silts. The gradual retreat of the ice barrier which held the lake in place afforded outlets at different levels, and at many of these stages the water remained long enough to form more or less distinct beach lines. A series of beach ridges

[1] Warren Upham, "Glacial Lake Agassiz," *U.S. Geol. Survey, Mono. No. 25.*

[2] W. A. Johnson, "The Genesis of Lake Agassiz," *Jour. Geol.*, XXIV (1916), 625–38.

were thus formed, the best developed of which commonly rise 10 to 20 feet above the adjoining surface on the side toward the former lake. They are composed of interstratified gravel and sand, and vary in width from 10 to 30 rods.

These beaches afford evidence of the elevation of the land to the north, since they are no longer horizontal, nor are they parallel, but show a divergence among themselves. All have a gradual ascent toward the north or northeast; the upper or Hermon beach, for example, rises 175 feet between Lake Traverse, at the south end of Lake Agassiz, and the international boundary. As these shore lines also show a divergence among themselves it is evident that this upward movement of the earth's crust began while Lake Agassiz was in existence and was probably largely completed before the lake was finally drained.

Sand and gravel deltas, so extensive as to constitute notable topographic features, were formed by the streams that flowed into Lake Agassiz while it stood at its highest stage. Those in North Dakota were formed by the Cheyenne, Pembina, and a Pleistocene river no longer in existence. Much of the finer sediment contributed to the lake by the inflowing streams was carried by the waves and currents and spread over the bottom of the lake as a fine silt. It is this fine loam, mingled with decayed vegetation, which forms the rich black soil of the Red River Valley, one of the great wheat regions of the world.

So recent is it geologically since the last ice sheet withdrew from North Dakota, and since Lake Agassiz was drained, that the drift surface and lake bed have been but slightly affected by erosion, and are still much as they were left at the close of the glacial period.

PEGMATITE, SILEXITE, AND APLITE OF NORTHERN NEW YORK[1]

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INTRODUCTION

During twelve seasons of field work in the Adirondack Mountain region of New York, the writer has made many hundreds of observations on bodies of pegmatite, quartz (silexite), and aplite. Certain of the phenomena long proved to be very puzzling, and more recently it has become evident that some generally accepted interpretations of such phenomena are not satisfactory when applied to many of the occurrences in the Adirondack region. While engaged in the detailed geologic mapping of the Lyon Mountain quadrangle, the writer was soon impressed by the exceptional opportunity for a careful study of the pegmatite, quartz (silexite), and aplite bodies which are there so wonderfully exhibited in countless numbers. Many detailed notes were taken and sketches were made. The North Creek quadrangle, surveyed by the writer some years ago,[2] was also revisited for the purpose of making further observations on certain pegmatites there so well exhibited. In this paper the discussions deal almost entirely with the Lyon Mountain and North Creek quadrangles.

PEGMATITE, SILEXITE, AND APLITE IN THE GRANITES OF THE LYON MOUNTAIN QUADRANGLE

The granites.—Several varieties of granite and granitic syenite constitute the main bulk of the rocks of this district. Among these the variety of chief interest in the present discussion is a fine to medium-grained, usually pink rock varying from a true granite through granitic syenite to quartz syenite or even quartz diorite. In the more typical specimens of granite dark minerals,

[1] Published by permission of the state geologist of New York.

[2] W. J. Miller, *N.Y. State Mus., Bull. 170.*

except magnetite, are either almost wholly absent, or they make up less than 5 per cent of the rock. Thin sections of the typical granites contain microperthite, 45 to 70 per cent; quartz, 25 to 35 per cent; oligoclase, 5 to 25 per cent; usually microcline, 5 to 15 per cent; magnetite, $\frac{1}{2}$ to 2 per cent; and usually less than 2 per cent of one or more of the following: titanite, hornblende or pyroxene, biotite, zircon, apatite, and hematite (stains). Locally, probably owing to incorporation of material from older basic rocks, dark minerals, including hornblende, monoclinic pyroxene, and biotite, are fairly conspicuous. A magmatic flow-structure foliation is generally more or less well developed in the granite, but some portions of the rock which are almost free from dark minerals exhibit practically no foliation to the naked eye.

The writer proposes to call the rock just described the "Lyon Mountain granite" because of the excellent exposures in and near the village of Lyon Mountain. This rock is also extensively developed on Johnson Mountain, Duncan Mountain, and in the valley of the Saranac River. The Lyon Mountain granite is perhaps the most conspicuous member of Cushing's "Saranac formation."[1] This Lyon Mountain granite contains a truly wonderful display of pegmatite and quartz (silexite) in the form of dikes, segregation masses, and inclusions. In many places the granite is very highly pegmatized. All the numerous magnetic iron-ore deposits, including those of the Lyon Mountain mines, occur in this granite. The structure and origin of these deposits are discussed by the writer in another paper.[2]

There is considerable field evidence to show that the Lyon Mountain granite grades into and is only a facies of a coarse-grained rock which the writer proposes to name the "Hawkeye granite" because of its excellent outcrops just east of Hawkeye post-office. In thin section the rock from the type locality shows microcline, microperthite, and quartz in about equal amounts; 8 to 10 per cent of oligoclase to albite; and small quantities of biotite, apatite, zircon, magnetite, chlorite, and secondary calcite.

[1] H. P. Cushing, *N.Y. State Mus., Bull. 95* (1905), pp. 299–303.

[2] W. J. Miller, *N.Y. State Mus. Bull.*, on the geology of the Lyon Mountain quadrangle soon to appear.

At the summit of Lyon Mountain the rock contains 2 or 3 per cent each of hornblende, diallage, and bronzite. The feldspar and quartz crystals are usually from one-fourth of an inch to an inch long. Where fresh the rock is greenish gray. It weathers to a light brown. A gneissoid structure is generally more or less well developed, though considerable bodies of the rock may show it scarcely at all. The Hawkeye granite is extensively developed in Silver Lake Mountain and in the southeastern half of the great mass of Lyon Mountain.

More locally the Lyon Mountain granite grades through granitic syenite into quartz syenite and even into quartz diorite.

Silexite in the granites.—The term "silexite" is elsewhere proposed[1] by the writer for any body of pure or nearly pure silica of igneous or aqueo-igneous origin which occurs as a dike, segregation mass, or inclusion within or without its parent rock. So-called "quartz dikes" are included under "silexite."

Hundreds of silexite masses were observed in the granites of the Lyon Mountain quadrangle. They are most abundant by far in the Lyon Mountain granite. The evidence that they are not true veins is decisive. None of them ever shows crustification, and many of them grade into true pegmatite. Thus at the summit of Duncan Mountain and also just south of the southern summit of Alder Brook Mountains, where both pegmatite and silexite are grandly exhibited in the large, bare ledges of Lyon Mountain granite, one may observe every possible gradation from typical, moderately coarse-grained pegmatite, consisting mostly of pink potash feldspar and some quartz, to about equal amounts of feldspar and quartz, to mostly quartz, with some scattering crystals of feldspar, and to practically pure silica (silexite). Most of the silexite contains 1 or 2 per cent of feldspar in the form of small crystalline masses with rather blurred contacts against the silica. All the facies just mentioned occur on Duncan Mountain, not only in the form of dikes more or less parallel to the foliation of the granite, but also often as irregular bunches or lenses crudely parallel to the foliation, the original masses in the latter cases apparently having been broken up, pulled apart, and the pieces

[1] W. J. Miller, *Science*, in a number soon to be issued.

more or less shifted after they were developed, by movements in the granite magma, which still possessed a considerable degree of fluidity. Such breaking up and shifting of pegmatite and silexite masses appear to have been most notably true of the silexite. Many of the later pegmatite dikes (below described) exhibit no such phenomena. We are led to conclude, therefore, not only that many masses of practically pure silica (silexite) separated from the granite magma well before many of the ordinary pegmatites, but also that the separation of the silica took place well before the complete solidification of the granite magma. Accordingly those masses of silexite which developed early (probably as segregation masses) and were broken up and more or less shifted in the magma are to be regarded as inclusions in the granite.

The following sketches (Figs. 1, 2, 3) of portions of the ledges at the summit of Duncan Mountain will suffice to make clear the foregoing conclusions. Figure 1 shows seven fragments of silexite. Evidently they represent portions of one or more masses which were broken up and strung out in the magmatic current. The wrapping of the magmatic flow-structure about the fragments is very evident. Contacts of the silexite against the granite are sharp. That these fragments are true inclusions of silexite which must have developed (probably by segregation) well before the final consolidation of the granite magma is strongly supported by the undoubted inclusions of both Grenville strata and an old gabbro which, in the Lyon Mountain district, have been observed to bear exactly similar relations to the granite (see Fig. 5). Unlike the Grenville and gabbro inclusions, however, the fragments of silexite are not distinctly older than the granite. They are early facies of the pegmatitic masses which developed during the intrusion of the granite and probably after the magma had come nearly to rest. Thus other nearby ledges of granite at the top of Duncan Mountain show distinct inclusions of silica which contain varying amounts of feldspar, though seldom more than 15 or 20 per cent. Usually with increased feldspar content the contacts against the granite are less sharp. Also in many cases silica, usually with a small content of feldspar, still exists in rather distinct dikelike form with only fairly sharp contacts against the granite. Again,

in many cases, practically pure silexite and ordinary pegmatite, the one grading into the other, occur in the same inclusion or dike. Just south of the southern summit of Alder Brook Mountains the large bare ledges contain many pegmatite and silexite masses which exhibit the features just described, the pegmatite and silexite there often grading into each other. Some of these cut the granite very irregularly in true dike form without very sharp contacts. Phenomena like those above described have been observed in many parts of the Lyon Mountain quadrangle.

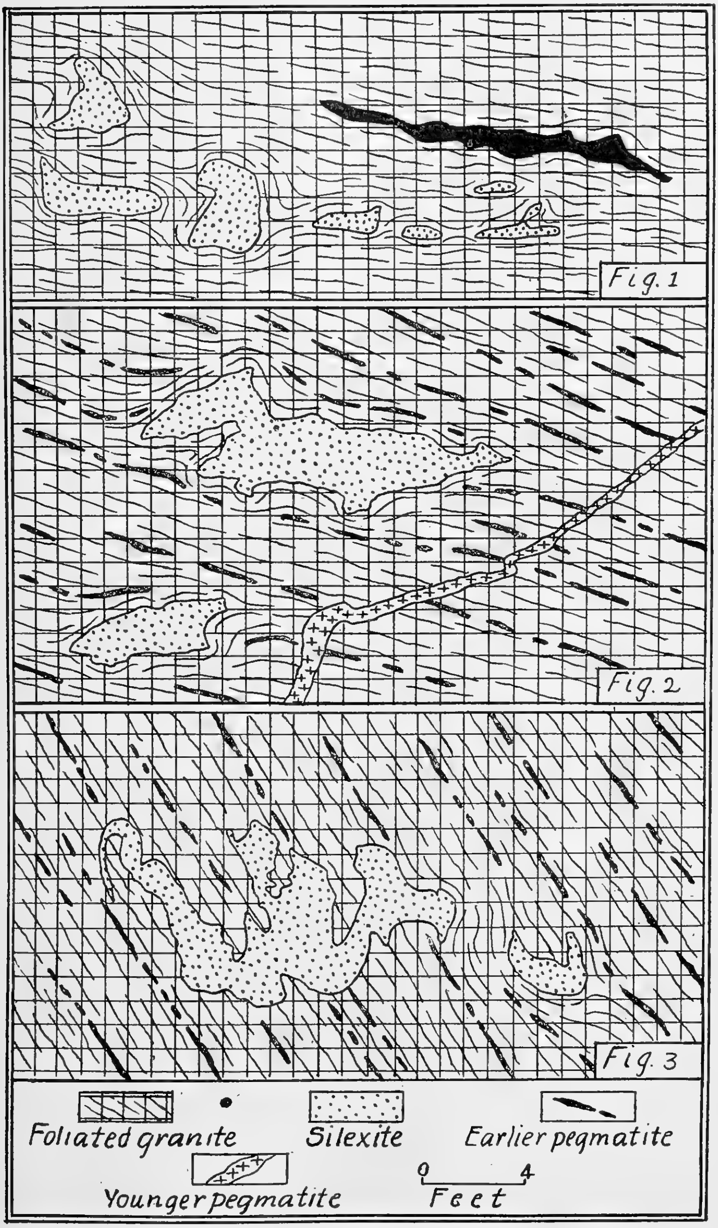
Figure 2 shows two larger masses of nearly pure silica (silexite) with their long axes parallel to the fluxion structure of the inclosing granite, with very distinct magmatic flow-structure foliation curved about them, and with sharp contacts against the granite.

A more exceptional case is shown by Fig. 3. The larger mass of silexite is exceedingly irregular in shape, and it locally contains considerable feldspar. Both inclusions seem to lie almost at right angles to the foliation of the granite, though it is quite possible that this ground-plan sketch does not actually represent the position of the whole original larger mass of silexite from which the inclusions were derived in the granite. Fluxion structure is locally distinctly curved on one side of the smaller fragment of silexite, and also between it and the larger fragment.

Figure 4 shows a very interesting silexite dike unusually thick at one end and with five clearly defined dikelike branches cutting the granite at the other end. The silexite contains not over 10 per cent of feldspar scattered through it in tiny masses. Contacts against the granite are only fairly sharp, and the foliation of the granite nowhere curves around the silexite. This is quite certainly a true dike of silexite, and it was formed later than the silexite of Figs. 1, 2, and 3, so it was not pulled apart by the granite magma which had already nearly or quite consolidated.

A small lens of silexite occurs as a distinct inclusion with sharp contacts in one of the later pegmatites (see below) on the low ridge one mile east-northeast of Goldsmith.

A mass of nearly pure silica (silexite) which demonstrably formed well before the solidification of the medium-grained granite which contains it occurs on the ridge one mile northeast of the



FIGS. 1, 2, and 3.—Sketches of portions of the ledges at the summit of Duncan Mountain in the Lyon Mountain quadrangle showing the relations of silexite and pegmatite to the foliated granite.

mouth of Two Brooks near Goldsmith. A lens of silexite was there pulled apart in the magma, some of which flowed into the intervening space. Contacts are sharp, and highly foliated granite occurs only close to the silexite.

Some interesting masses of silexite of relatively late origin occur in slightly foliated quartz syenite on the hill half a mile north of Mud Pond near Riverview. South of the summit of this hill several dikes of silexite contain very little feldspar, and they lie parallel to the foliation of the syenite, without sharp contacts. About 40 rods east of the summit of the hill a pegmatite dike 10

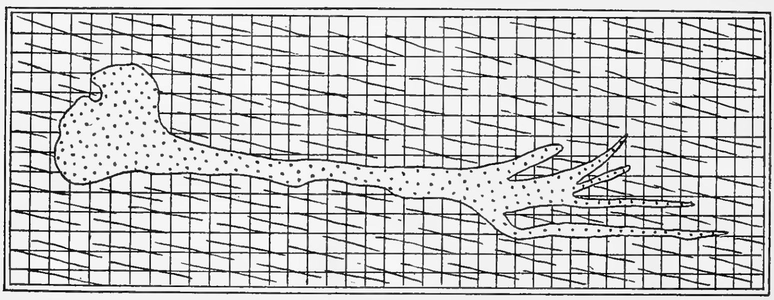


FIG. 4.—A mass of silexite 28 feet long with branching dikes in the granite on the ridge one and two-thirds miles north-northeast of Union Falls in the Lyon Mountain quadrangle.

inches wide and 15 feet long grades into the quartz syenite on either side and lies parallel to the foliation. The middle of the dike or segregation mass is nearly pure silica (silexite) which grades into the pegmatite. Near by a coarse-grained pegmatite dike several feet wide cuts obliquely across the foliation, this dike therefore belonging with the latest pegmatites below described.

Figure 5 represents a small portion of a belt of granite 25 to 30 feet wide and 100 feet long which contains many angular inclusions of silexite and Grenville quartzite and schist. All the inclusions have sharp contacts, and they mostly have their long axes roughly parallel to the magmatic flow-structure foliation which tends to curve about them. Masses of nearly pure silexite of very early origin were here pulled to pieces, and the pieces were moved in the still fluid granite.

Some fine examples of crudely lens-shaped masses of practically pure silica (silexite) have been observed by the writer in the Blue Mountain quadrangle in syenite, granite, and mixed gneisses apparently always parallel to the foliation of the inclosing rock. In one case a small dike of pegmatite sharply cuts a long, narrow lens of silexite.

Earlier pegmatites.—A great many masses of true pegmatite of early origin lie in the Lyon Mountain granite parallel to its

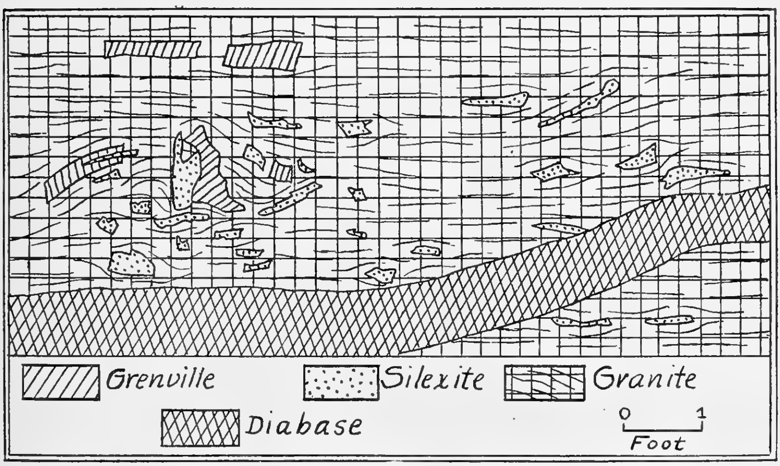


FIG. 5.—Angular inclusions of both silexite and Grenville quartzite in foliated granite at the top of the hill one-third of a mile south-southwest of Barnes Pond in the Lyon Mountain quadrangle.

foliation. The mineral content of these early pegmatites is remarkably simple, by far the greater number of them consisting very largely of quartz and potash feldspar (mostly microcline), some microperthite and oligoclase, and a little biotite. Some pegmatites, probably to be classed with the early ones, though not with the earliest, carry more or less magnetite, hornblende, or pyroxene, but these minerals appear to have been largely or wholly derived from the old dark gneisses and gabbro which were invaded by the granite. Minerals so common to pegmatites in general, such as tourmaline, garnet, muscovite, beryl, apatite, and others, must be exceedingly rare if they occur at all. The only mineralizer,

therefore, which could have been present in very appreciable quantity during the crystallization of these pegmatites was water. These pegmatites rarely if ever show graphic intergrowths.

In many localities from 10 to 50 per cent of the body of the granite consists of the earlier pegmatite either in the form of narrow parallel bands from a few feet to many feet long, causing the rock to look like a coarse-banded gneiss, or as rather distinct lenses up to several feet long; or in the form of "eyes" or very short, thick, more or less rounded or elliptical lenses usually not more than a few inches long and from one-half to two or three inches thick. The long, narrow bands almost invariably grade into the granite on either side, while the lenses and eyes generally show moderately sharp contacts against the granite. The mode of occurrence of such eyes of pegmatite is fairly well illustrated by Figs. 2 and 3, the granite containing the eyes, usually exhibiting rather wavy flow-structure foliation about them. From the field relations it is quite certain that the eyes and short, rounded lenses represent long lenses or layers of pegmatite which formed before the final consolidation of the inclosing granite, and which were pulled apart and strung out parallel to the magmatic currents which were deflected around them. Their mode of occurrence and lack of sharp contacts strongly suggest that they formed during a late stage of magma consolidation, and that they are not so old as the oldest silexite masses, which are now represented as sharply defined inclusions.

M. E. Wilson,[1] in a description of the gneisses of the Laurentian highlands, notes apparently similar lenses of pegmatite and says that a "lenticular character is particularly evident in the case of the pegmatite which commonly occurs in a succession of lenses around which the foliation of the surrounding gneiss bends."

Those pegmatites which occur as long, narrow, irregular bands or strips parallel to the granite foliation, and which grade into the granite, no doubt represent the final or nearly final solidification of those portions of the granite in which they occur, and hence they are practically *in situ* and grade into the granite. Figure 1 shows a single lens of such pegmatite.

[1] M. E. Wilson, *Amer. Jour. Sci.*, XXXVI (1913), 115.

A typical example bringing out the relation of the earlier to the later pegmatites occurs in a big ledge on the little hill just south of the mouth of Two Brooks near Goldsmith. Much of the granite contains streaks, lenses, and eyes, usually less than an inch wide and not over two feet long, of not very coarse pegmatite parallel to the foliation. This pegmatite makes up a very considerable percentage of the rock mass, with contacts varying from fairly sharp to not sharp. Cutting this combination of granite and pegmatite are several prominent later pegmatite dikes, six to eight feet wide and forty or fifty feet long, carrying equal amounts of quartz and feldspar and 10 per cent of biotite. These moderately coarse-grained later pegmatite dikes lie only partly roughly parallel to the granite foliation. This ledge calls to mind an exposure observed by the writer in the Blue Mountain quadrangle,[1] where lenses and eyes of pegmatite parallel to the foliation of a mixed gneiss are sharply cut across by a pegmatite dike of distinctly later origin.

On a little ridge one mile east-northeast of Goldsmith an outcrop shows two bands or long lenses of pegmatite parallel to the foliation of the granite and without very sharp contacts. The upper lens consists of two-thirds quartz and one-third feldspar, and it is very uniform. The lower lens is notably variable, with the different portions not sharply separated. Nearly pure silica (silexite) and typical pegmatite here developed side by side, while the inclosing granite was still somewhat fluid, as shown by the flow-structure along the lower side of the lens.

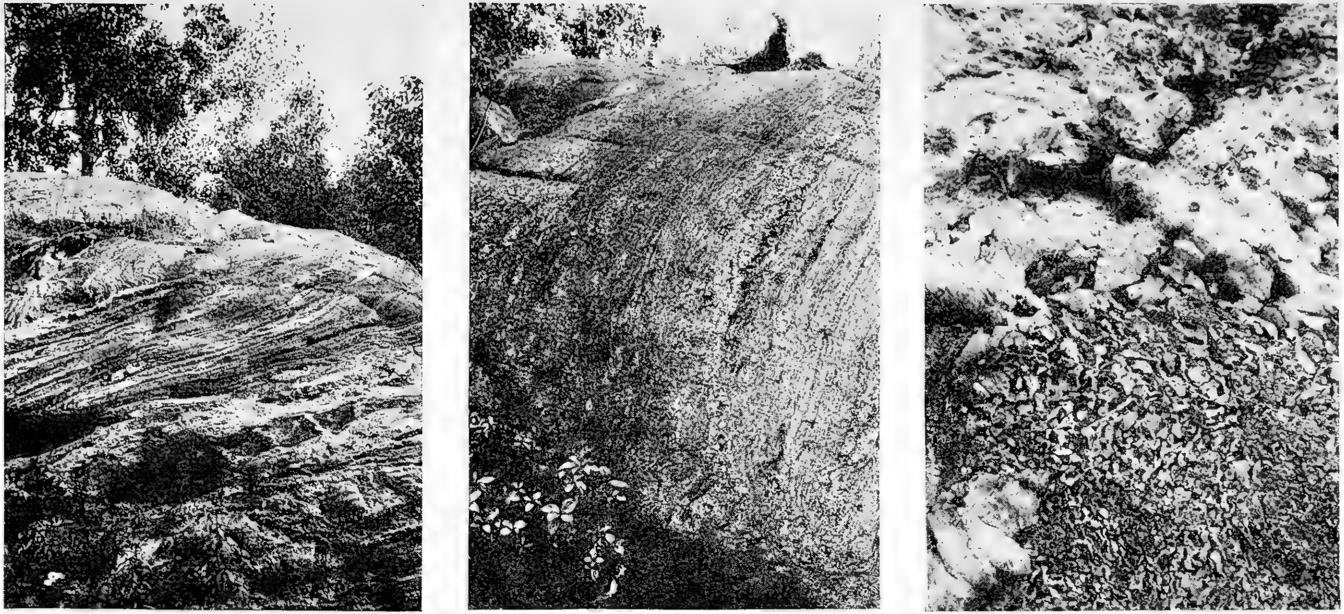
Near the road two miles east-southeast of Goldsmith a pegmatite dike, or rather a segregation mass, one foot wide and twelve feet long, which lies parallel to the foliation of the inclosing granite and grades perfectly into it, shades off into a zone of nearly pure silica (silexite) four to five inches wide toward its middle. Both the pegmatite and the silexite here developed side by side by segregation during a late stage in the solidification of the granite magma, and both pegmatite and silexite now occupy practically the place where they solidified.

A more exceptional mode of occurrence of the older pegmatites is illustrated in a ledge by an old road one mile northwest of the

[1] W. J. Miller, *N.Y. State Mus., Bull. 192* (1916), pl. 10.

mouth of Alder Brook. One mass of pegmatite a few feet wide perfectly exposed for twenty feet contains orthoclase crystals up to three or four inches long, and its boundaries against the granite are sharp. A very evident magmatic flow-structure follows the details of the very irregular boundary on either side within six inches of the pegmatite, but one or two feet out the foliation is practically straight. Evidently this typical pegmatite developed unusually early, probably by segregation, perhaps as early as some of the first-formed silexite, that is to say, when the granite magma still possessed a considerable degree of fluidity.

Later pegmatites.—As regards their mode of occurrence these later pegmatites are in most respects quite ordinary. They cut across the granite foliation at all sorts of angles, and hence they must have developed after complete, or at least almost complete, solidification of the granite which contains them. They are true dikes, generally coarser grained and usually larger than the older pegmatite masses above described. Many of them are from one to ten feet wide and from ten to fifty feet or more long. They rarely if ever exhibit graphic intergrowths. Contacts against the granite range from very sharp to moderately sharp, those with very sharp boundaries probably having developed in the solid, relatively cooler granite, while those with less sharp boundaries probably were intruded into essentially solid but relatively hot granite. Most of these dikes consist largely or wholly of pink or white potash feldspar and quartz; some contain hornblende or pyroxene, or both; some contain little or no quartz; some are almost pure quartz (silexite); a few contain scapolite, and many contain magnetite in amounts ranging from 1 to 40 or 50 per cent. With few exceptions these later pegmatites, like the earlier ones, do not contain any other minerals as well known in pegmatites in general. As pointed out below, the hornblende, pyroxene, and magnetite were almost certainly absorbed by the pegmatites from the old, invaded dark gneisses and gabbro. Apatite in small amount and many specks of titanite occur in some of the pegmatized zones of the granite in the main workings of the iron mine at Lyon Mountain village, and in somewhat greater amounts in the older workings to the east. Throughout the Lyon Mountain



A B C

FIG. 6.—A: Part of ledge one and one-fourth miles north of Disco in the Lyon Mountain quadrangle showing hornblende gneiss (probably meta-gabbro) more or less intimately injected with Lyon Mountain granite, the resulting mixed rock being cut by pegmatite and silexite. Silexite is well shown toward the middle of the picture and pegmatite just below the middle, the latter sending dikes across a large lens of the dark gneiss. Owing to pegmatization, much of the hornblende of the dark gneiss has been changed to pyroxene. The folding toward the top was caused by magmatic movement. Width of exposure about 15 feet.

B: Part of a ledge one mile east of Goldsmith in the Lyon Mountain quadrangle. The finer-grained portion is Grenville biotitic and quartzitic gneiss intimately injected with Lyon Mountain granite. The nearly white lenses and narrow strips are pegmatite and silexite developed during an early stage of the magma consolidation, and the broad band is pegmatite which formed late in the process of the magma solidification. Width of exposure about 15 feet.

C: Near view of part of the mass of pegmatite on the western side of the gabbro stock on the hill one mile south-southeast of the Glen in the North Creek quadrangle (see Fig. 8). Lower half is quartz and black tourmaline graphically intergrown, and upper half is mostly silexite. Width of exposure about 2 feet.

quadrangle, however, even these minerals are very rare or absent. Aside from water vapor, then, these later pegmatites must have been mostly relatively free from mineralizers.

Figure 2 shows one of the later pegmatites with fairly sharp contacts cutting across a ledge of granite which contains inclusions of silexite and eyes or inclusions of older pegmatite.

Near the top of the hill two miles east of Goldsmith a distinctly later pegmatite dike not only cuts across the foliation of the granite but also sharply cuts earlier-formed lenslike masses of both pegmatite and silexite.

Just south of the southern summit of Alder Brook Mountains several dikes of ordinary pink pegmatite grading into practically pure silexite cut the granite in all directions without very sharp contacts.

A fine ledge clearly exhibiting the relations of earlier pegmatite and silexite to later pegmatite occurs on the little hill one-fourth of a mile northwest of the mouth of the eastern of the Two Brooks near Goldsmith. Thin-bedded Grenville quartzite and gneiss are mostly highly injected with medium-grained granite, pegmatite, and silexite. This combination of rocks is locally much contorted, owing to magmatic movements, and the pegmatite and silexite, especially the latter, are much broken up and kneaded into the mass, thus proving that this pegmatite and silexite originated before the solidification of the granite magma. Ordinary pegmatites cut across this ledge of mixed rocks in true dikelike form at various angles, and they are not broken up, thus clearly indicating their distinctly later origin, that is, after the solidification, or at least almost complete solidification, of the granite magma.

Before leaving the consideration of the later pegmatites, the occurrence of magnetite, hornblende, and pyroxene in many of them should be briefly discussed. One or more of these minerals may be observed in the later pegmatites of the Lyon Mountain quadrangle in many places, but almost invariably only where the pegmatites are known to be directly associated with an older hornblende gneiss or gabbro, though not all the pegmatites thus associated contain one or more of the minerals mentioned. The

field evidence strongly points to a derivation of these minerals from the older basic rocks by the pegmatites during their intrusion. It is significant that more or less magnetite occurs in later pegmatites at every one of the dozen or more localities from which magnetic iron ore has been mined in the Lyon Mountain quadrangle and also at many other places. A few of the more typical field occurrences will now be briefly described.

In the old mine at Russia Station pink granite and pegmatite have been intimately injected into more or less hornblende gneiss (presumably gabbro), and much of the hornblende has been altered or recrystallized into green monoclinic pyroxene, some of which occurs locally in the form of coarse granular masses several inches across. Magnetite is variably abundant in all the rocks, but it is especially so in the coarser pegmatites and the silexite of later origin which occur as rather well-defined dikes.

On the ridge one and one-half miles northeast of Standish a very irregular pegmatite dike, with a maximum width of thirty feet and traceable for one hundred and fifty feet, lies in contact with gneissoid gabbro. The pegmatite is moderately coarse to very coarse and is very rich in magnetite, many masses of which are from one to three inches across. Some tongues of the pegmatite rich in magnetite cut across the foliation of the gabbro.

On Elbow Hill two miles east-northeast of Lyon Mountain village a pegmatite dike ten feet wide and thirty feet long is directly associated with a mixture of granite and gneissoid gabbro. This pegmatite is practically a silexite, being very rich in quartz and low in feldspar, and it contains much magnetite in masses up to several inches across. The magnetite and quartz appear to be of the same generation. Some of the more ordinary later pegmatites close by contain little or no magnetite.

In one of the ore pits near the western end of the main workings at Lyon Mountain a pegmatite dike from one to two feet wide and exposed for seventy-five feet rather sharply cuts intricately mixed pink granite and hornblende gneiss. This pegmatite carries little or no quartz, but it does contain some magnetite.

By the river one mile south-southeast of Moffitsville later pegmatite cuts intricately involved granite and hornblende gneiss,

the pegmatite containing bunches of green, monoclinic pyroxene and hornblende which look like inclusions up to five inches across. The pyroxene developed by recrystallization of some of the hornblende of the hornblende gneiss during the process of pegmatization for all stages, from bunches and lenses of pure hornblende, to mixtures of hornblende and pyroxene not sharply separated, to pure pyroxene, occurs in the pegmatite. Also, in thin section every stage in the transformation of the hornblende to pyroxene has been observed. This pegmatite carries some magnetite and in one portion scattering single crystals of hornblende up to one inch long, and in another portion crystals of pyroxene up to one-half of an inch long.

Aplite dikes.—Aplite dikes are locally developed often in considerable numbers in the coarse or Hawkeye type of granite. It is a striking fact that nowhere in the quadrangle were aplite dikes observed in the typical Lyon Mountain granite which contains such a profusion of pegmatites and silexites. Possibly this is because the Lyon Mountain granite is itself locally rather aplitic in character. Since the Hawkeye granite contains relatively few pegmatite and silexite masses, such could seldom be observed in their relations to the aplites in single outcrops. Few if any aplites occur in the granitic syenite or quartz syenite. It should here be recalled that the field evidence strongly points to development of the Lyon Mountain granite, Hawkeye granite, granitic syenite, and quartz syenite from a single intrusive magma in the Lyon Mountain quadrangle.

Nearly all the aplites of the quadrangle are in the form of more or less well-defined dikes which are very uniform in composition, consisting of white or light-gray potash feldspar, microperthite, and quartz with almost no accessory minerals. In a few cases dark minerals occur in moderate amounts.

Most of the aplite dikes by far lie more or less perfectly parallel to the foliation of the coarse granite, but a considerable number cut across the foliation at various angles. Not uncommonly the cross-cutting dikes are branches of those which are parallel to the foliation. Contacts of the aplites against the granite are rarely sharp, though the transition generally takes place within an inch or two. Some of the aplite dikes, more especially the wider ones,

exhibit good magmatic flow-structure foliation. No case of an aplite dike grading into pegmatite was observed, though one example of gradation to silexite was noted. The aplite dikes usually vary from one or two to several feet wide and ten to twenty-five feet long, but some are considerably larger.

The field evidence strongly indicates that all or nearly all the aplites developed during a very late stage of the consolidation of the Hawkeye granite magma, as shown by the common parallelism to the foliation and the lack of very sharp contacts. There is no evidence, such as that above presented, that any of the aplites formed as early as the earliest of the pegmatite and silexite masses, and there is positive evidence that some, and strong probability that many, of the latest pegmatites were intruded after the aplites. Considering the time then during which the pegmatite and silexite masses developed, the aplites are intermediate and the length of time for their development was distinctly shorter. Descriptions of a few selected examples will serve not only to show the nature of the evidence upon which the foregoing conclusions are based, but also to bring out certain other features of interest.

A fine display of aplite dikes may be seen on the ridge one-half of a mile southeast of Hawkeye post-office. Contacts against the typical coarse granite are not sharp, but the transition takes place within an inch. The dikes show all widths up to three feet. Most of them roughly follow the foliation of the granite, but some cut across at low angles and a few at high angles. One dike lies at right angles to the foliation for about fifteen feet and then gradually swings into parallelism with it. A few rods east of this locality some lenses of aplite a few feet long occur with somewhat sharper contacts against the granite. This suggests an earlier development of aplite masses, either as segregation masses or as dikes, which were pulled apart and somewhat strung out in the form of inclusions in the still moderately fluid magma. On the ridge one-sixth of a mile northeast of the first-named locality an aplite dike twelve to eighteen inches wide and exposed for forty feet cuts diagonally across the foliation of the coarse granite without sharp contacts. Almost exactly in its middle there are two masses of silexite fifteen feet long and a few inches wide, with no

very sharp contacts against the aplite. This silexite resulted from differentiation practically in the place where it now occurs.

On the eastern summit of Howard Mountain an aplite dike about one foot wide lies parallel to the foliation of and grades into the coarse granite on one side, but it has a fairly sharp contact on the other, this latter contact evidently being a result of some magmatic flowage along the border of the aplite after its development.

On the hill one and one-half miles southwest of Sugarbush post-office a distinctly foliated aplite dike with a maximum width of fifteen feet and traceable for one hundred feet pinches out at one end and everywhere grades into the coarse granite within an inch.

At the top of Averill Peak a number of aplite dikes up to one foot wide lie in the coarse granite parallel to its foliation and without sharp contacts. Some ordinary pegmatites of the late series cut right across these aplites. Several aplite masses ten to twenty feet long occur as lenses without very sharp contacts against the granite.

On a spur of Lyon Mountain one mile east-southeast of its summit a number of aplite dikes from one to two feet wide mostly lie roughly parallel to the foliation of the coarse granite, but some cut across at various angles. These dikes carry some dark minerals, are without sharp contacts against the granite, and are usually foliated parallel to their borders. Several of them contain distinct inclusions of the coarse granite in the form of lenses one or two feet long, without sharp contacts against the aplite and parallel to its foliation. The granite must have been almost or quite solidified before the aplitic magma entered.

One-half mile north of the last-named locality one small aplite dike cuts another without sharp contacts against either aplite or coarse granite. Thus there were two distinct intrusions of aplite not far apart in time.

Conclusions regarding pegmatite, silexite, and aplite in the granites.—Some of the main conclusions from the foregoing observations are as follows:

1. The Lyon Mountain granite and the Hawkeye granite are believed to have developed from a single body of intruding magma.

2. The Lyon Mountain granite contains a great profusion of silexite and pegmatite masses, while the Hawkeye granite contains relatively few.

3. The Hawkeye granite contains many aplite dikes, but none at all was observed in the typical Lyon Mountain granite.

4. By far the greater number of the pegmatites, both the earlier and the later types, consist almost wholly of quartz and alkalic feldspar. With a few local exceptions minerals which indicate the former presence of mineralizers other than water vapor are practically absent.

5. Silexite masses began to develop, probably as segregation products, while the granite magma still possessed a very considerable degree of fluidity, and they continued to form probably both as segregation products and as dikes, until the inclosing granite almost, or possibly completely, solidified.

6. Pegmatite masses also began to develop well before the solidification of the magma, though probably not as early as the earliest silexite masses, and they continued to form until almost, or possibly complete, consolidation of the inclosing granite.

7. The silexite masses represent very siliceous facies of the pegmatitic development, gradations from nearly pure silica to ordinary pegmatite being not uncommon.

8. By far the greater number of the pegmatites, silexites, and aplites occur within the parent granites, though some also occur in the relatively small remnants of the rocks into which the granites were intruded.

9. The aplites were developed during a late stage of the magma consolidation, none as early as the earliest pegmatites and silexites, and probably none as late as the latest pegmatites. Some aplites cut others, thus proving intrusions distinctly different in time.

Authors of practically all the standard works on petrology definitely regard pegmatites as intrusions into the already solidified portions of the magmas from which they were formed. Iddings[1] says that pegmatitic liquid may be made to "flow into openings formed by the fissuring of completely solidified parts of the magma,

[1] J. P. Iddings, *Igneous Rocks*, I (1908), 272.

chiefly the outer portions." According to Harker,[1] "the pegmatite may in any case be regarded as representing the residual 'mother liquor' at the end of the process of crystallization." Pirsson[2] states that pegmatite dikes form "in the already solidified parts of the igneous mass." In an important paper on the origin of pegmatite Crosby and Fuller[3] say: "Pegmatite is the end product or final crystallization of the original magma." Brögger[4] considers certain Norwegian pegmatites as representing the last stage of the consolidation of the granite magma. Such statements as the preceding may hold for many of the pegmatites and silexites of the world, but the writer's conclusions (Nos. 4 and 5 above) regarding the pegmatites and silexites of the Lyon Mountain district are notably different, that is to say both pegmatite and silexite began to develop while the parent magma was still in a relatively highly fluid state.

It is also commonly stated or assumed that pegmatites and silexites always developed in the form of dikes. But from the evidence above presented for the Lyon Mountain district, it is concluded that many of the pegmatite and silexite masses, especially those of earlier origin, developed as magmatic segregation products because they formed while the inclosing granite was still magmatic with a considerable degree of fluidity, and it is difficult if not impossible to understand how pegmatite and silexite in the form of true dikes could have intruded such a magma.

For the comparatively few districts in which silexites have been carefully studied it is commonly held that where pegmatite and silexite have both developed from a granite magma the silexite solidified last. As Iddings[5] says: "The association of these quartz rocks with pegmatite is such that in many instances they appear to be portions of the magma segregated from the rest and the last to crystallize." Spurr[6] reaches the same conclusion after

[1] A. Harker, *The Natural History of the Igneous Rocks* (1909), p. 296.

[2] L. V. Pirsson, *Rocks and Rock Minerals* (1909), p. 175.

[3] W. Crosby and M. Fuller, *Amer. Geol.*, XIX (1897), 165.

[4] W. C. Brögger, *Zeit. für Kryst.*, XVI (1890).

[5] J. P. Iddings, *Igneous Rocks*, II (1913), 28.

[6] J. E. Spurr, *U.S. Geol. Surv., Prof. Paper 55* (1906), p. 115.

a careful study of the quartz of magmatic origin in the Silver Peak district of Nevada. In the Lyon Mountain district, however, the writer finds that silexite masses began to develop not only well before the consolidation of the parent granite magma, but also apparently even before the earliest of the pegmatites.

It is also a matter of common record that pegmatites are either absent from, or relatively uncommon in, their parent igneous body, while they are relatively abundant in the country rocks. Grout[1] has recently cited a number of the many well-known examples. In the Lyon Mountain district, however, pegmatite and silexite masses are extremely abundant in the parent granite, and they are certainly not more common in the relatively small portions of the intruded country rocks which still remain.

Finally many districts show ordinary pegmatite dikes close to or in the granite, and, traced outward into the country rocks, the pegmatites become more and more siliceous, being practically silexite dikes or quartz veins farthest out. As Pirsson[2] says: "Finally passing onward the solution phase might become more pronounced, only silica would be carried, and the dike turn into a quartz vein." Van Hise,[3] in the Black Hills, and Emerson,[4] in western Massachusetts, found pegmatite dikes in schist near granite, and farthest out silexite dikes or quartz veins. But in the Lyon Mountain district such a relationship does not hold, since typical pegmatites and silexites in many places occur side by side in the parent granite, and in some cases both form parts of individual dikes or segregation masses.

PEGMATITES IN THE GABBRO OF THE NORTH CREEK QUADRANGLE

Some years ago the gabbro masses of the North Creek quadrangle were discussed at considerable length by the writer.[5] The very common if not constant close association of pegmatites with

[1] F. F. Grout, *Econ. Geol.*, XIII (1918), 180–90.

[2] L. V. Pirsson, *Rocks and Rock Minerals* (1909), p. 180.

[3] C. R. Van Hise, *U.S. Geol. Surv., Mon. 47* (1904), p. 724.

[4] B. K. Emerson, *U.S. Geol. Surv.*, Folio 50, 1896.

[5] W. J. Miller, *Jour. Geol.*, XXI (1913), 160–80; *N.Y. State Mus., Bull. 170* (1914), pp. 26–28.

the gabbro was then mentioned, but no special study of the pegmatites was made. In 1918 the region was revisited, and the relations of the pegmatites to the gabbro were studied in detail. The gabbro nearly always occurs in the form of stocks or bosses with rounded or elliptical ground plans. The stocks range in length from a few rods to about a mile and in width up to three-fourths of a mile. That most if not all of the gabbro stocks are younger than the syenite-granite series is proved by the many observed sharp contacts often crossing the foliation of the syenite or granite, by many inclusions of syenite and granite in the gabbro, and by some dikes of gabbro which extend into the syenite-granite series.

The field evidence strongly points to the mode of occurrence of the gabbro as pluglike or pipelike forms with nearly vertical boundaries. Much of the gabbro is of the quite typical sort, consisting chiefly of basic plagioclase, some orthoclase, hornblende, and hypersthene, together with almost constant small amounts of ilmenite (or magnetite), biotite, garnet, and pyrite, and some other accessory minerals. An ophitic texture is often well exhibited. Many of the stocks have foliated portions, especially the borders, which are hornblende gneiss or amphibolite.

The pegmatites are mostly coarse-grained, consisting chiefly of potash feldspar and quartz, but with plagioclase important in some cases, muscovite and black tourmaline usually present, and biotite and hornblende not rare. Practically no other minerals occur. The masses of pegmatite exist in all sizes up to two hundred or more feet long and fifty or more feet wide.

Very few of the many conspicuous bodies of pegmatite of the kind just described were observed apart from masses of gabbro in the North Creek quadrangle, and possibly even these few may not be real exceptions, because the adjacent rocks are not always wholly known on account of lack of exposures. Pegmatites of any kind are relatively scarce in the syenite-granite series. Since most or all of the gabbro stocks are younger than the syenite-granite, and since so many of the coarse, acidic pegmatites either cut the gabbros or are at least genetically related to them (see below), it follows that such pegmatites must be distinctly younger

than the syenite-granite series. Pegmatites seldom if ever occur well within the larger areas of gabbro, and it seems that they formed as satellites of the gabbro mostly in the marginal portions of the stocks and to some extent at least in the closely adjacent rocks.

There are two features of special interest regarding these pegmatites: first, that they are satellitic developments of rather

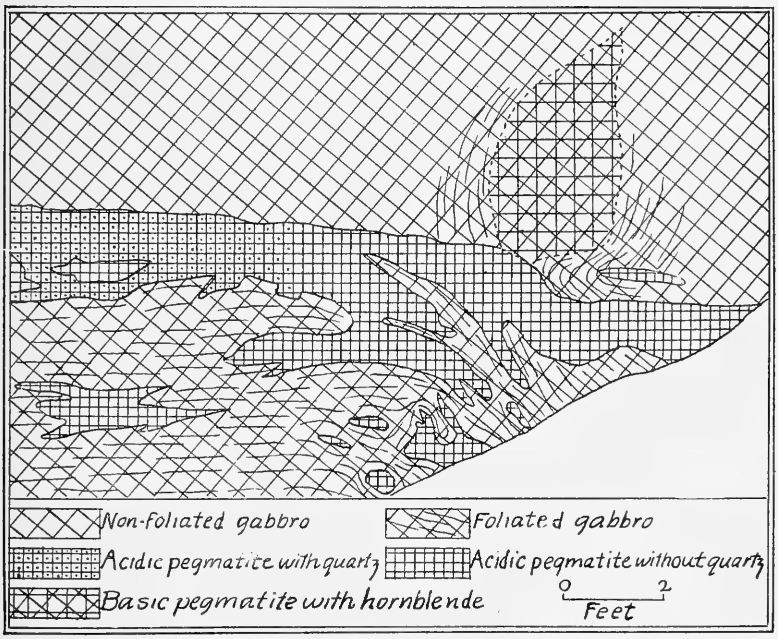


FIG. 7.—Sketch showing the relations of several facies of pegmatite to gabbro at the northeastern edge of the stock on the hill one mile south-southeast of the Glen in the North Creek quadrangle.

basic gabbro, and, secondly, that the evidence strongly points to the development of many of them while the parent magma still possessed a considerable degree of fluidity. The following descriptions and figures of selected examples will serve to make clear the principal phenomena of the pegmatites in their relations to the gabbros.

One of the best places in the North Creek quadrangle to study the relation of pegmatite to the typical gabbro is at the top of the

hill one mile south-southeast of the Glen. The gabbro stock, which is one-fourth of a mile long, shows a number of pegmatitic satellites, and that it is younger than the surrounding granite is proved by several inclusions of the latter. Figure 7 illustrates the relations of several facies of the pegmatite to the gabbro near the northeastern edge of the stock. Crystals in any of the pegmatite seldom reach lengths of an inch. The acidic pegmatite with quartz carries biotite, and it grades perfectly into the rather acidic pegmatite without quartz but with hornblende. In both of these facies of the pegmatite the chief feldspar is oligoclase to oligoclase-albite. Contacts against the gabbro are usually rather sharp. The more basic pegmatite, which consists chiefly of basic plagioclase and hornblende with some magnetite, shows no sharp contact against either the acidic pegmatite or the gabbro. That the various facies of the pegmatite formed while the gabbro magma was still in a distinctly fluid condition is considered to be proved, not only by the presence of well-defined inclusions of the pegmatite mostly parallel to the magmatic flow-structure of the gabbro, but also by the strong tendency of the fluxion structure of the gabbro to wrap around the inclusions and to conform to the sides of the large body of pegmatite. Quite clearly the molten gabbro intruded and more or less broke up the already consolidated pegmatite which had probably developed as a magmatic segregation mass. The basic pegmatite may have developed somewhat later than the other, as suggested by the lack of anything like sharp contacts against the gabbro, but even this pegmatite formed while the gabbro was still fluid enough to develop a fluxion structure alongside the pegmatite.

Near the middle western edge of the same gabbro stock a pegmatite mass, with a maximum width of twenty-five to thirty feet and an exposed length of about one hundred feet, shows relations notably different from those on the opposite side of the stock above described. Some of the features are brought out by Fig. 8. Toward one side of the general body of pegmatite a mass of practically pure silica (silexite) has imbedded in it many rather imperfect crystals of black tourmaline which mostly range in length from one to ten inches. This small mass is surrounded by very coarse pegmatite made up chiefly of potash feldspar and quartz with a little tour-

maline, the feldspars reaching lengths of a foot or more. Inclosing both masses just mentioned is a body of coarse pegmatite, which is the most abundant facies of the rock. The feldspar all seems to be orthoclase in crystals, with maximum lengths of six or eight inches. Quartz is abundant, and hornblende crystals up to several inches long are fairly common. There are also exceptionally fine graphic intergrowths of tourmaline and quartz in masses from a few inches to a foot or more across (Fig. 6C). Along one side of the coarse pegmatite there is a zone roughly five or six feet wide of only moderately coarse pegmatite which consists chiefly of potash feldspar and quartz with some acidic plagioclase and biotite. Adjacent to this moderately coarse pegmatite and forming the outside of the whole mass of pegmatite on one side is a zone several feet wide of moderately coarse pegmatite made up very largely of plagioclase which contains some microcline as graphic intergrowths and a little quartz. This plagioclase zone merges into the true gabbro through a zone about a foot wide. None of the five facies of pegmatite just described are at all sharply separated from each other, and they are very clearly phases of a single pegmatite body. The relation of the pegmatite to the gabbro on the opposite side of the whole body of pegmatite is not so well shown, but there appears to be a gradation within an inch or two. On either side of the pegmatite body the gabbro is non-foliated. Similar relations to the gabbro are exhibited where the pegmatite body extends fifty feet northeastward, ending in broad tongues in the gabbro. There, however, the plagioclase zone is seven or eight feet wide, and it contains considerable quartz and some biotite. One mass of gabbro five feet across is surrounded by pegmatite with a fairly sharp contact on one side and a gradation on the other.

The assumptions that this whole body of pegmatite was a distinctly later satellitic development of the gabbro than that above described as occurring on the opposite side of the same stock, that the gabbro must have been almost or quite solidified before it formed, and that the five facies of the pegmatite were probably formed by some sort of differentiation practically in the place of their present occurrence are evidenced by the following facts: gradation of the borders of the pegmatite into the gabbro,

an inclusion of the gabbro in the pegmatite, lack of magmatic flow-structure foliation in the gabbro near the pegmatite, and perfect gradation from one facies of the pegmatite into another.

Along the northwestern side of the same gabbro stock there are several small pegmatite masses, one with fairly sharp contacts and the other without. Also a number of rather rounded masses of basic pegmatite (chiefly plagioclase and hornblende) from one to several feet across appear to be inclusions, with fairly sharp contacts, in foliated gabbro. Such pegmatite must have formed

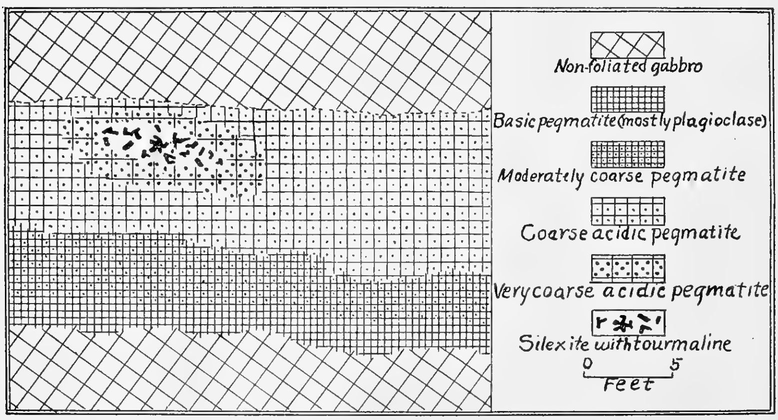


FIG. 8.—Sketch showing several facies of pegmatite in the gabbro at the western edge of the stock on the hill one mile south-southeast of the Glen in the North Creek quadrangle.

while the gabbro was still molten. A few rods farther north a small dike of acidic pegmatite with rather sharp contacts has an aplitic offshoot three inches wide which bears off abruptly for twelve feet into non-foliated gabbro, with fairly sharp contacts against the latter.

On the southern side of the small stock one and one-fourth miles north of the Glen several moderately coarse acidic pegmatite masses from three to twelve feet long lie in the gabbro, with fluxion structure of the latter parallel to the borders of the pegmatite, but only close to them. Contacts against the gabbro are rather sharp. Well within the stock several small inclusions of the country rock (granite) also lie in the gabbro parallel to a magmatic

flow-structure foliation of the latter. Clearly, then, these acidic pegmatites are not only satellites of the gabbro but also formed, probably by magmatic segregation, well before the gabbro magma was consolidated. Another body of pegmatite about six feet wide in this gabbro grades into a mass of practically pure silica (silexite) four feet long.

A large body of pegmatite exposed for two hundred and fifty feet lies on the east side of the gabbro stock near the top of the hill three and one-half miles south-southeast of Chestertown. This pegmatite is mostly orthoclase and quartz in masses up to a foot or more across, together with considerable muscovite, biotite, and tourmaline in masses up to several inches across. In an old mine pit a moderately coarse facies of this pegmatite containing some plagioclase is intricately involved with a highly foliated feldspar-biotite schist phase of the gabbro which grades perfectly through a fine-grained foliated gabbro into normal, medium-grained, non-foliated gabbro. The zone of mixed rocks, which is forty to fifty feet wide, contains many long lenses, strips, and irregular masses of pegmatite arranged roughly parallel to the fluxion-structure foliation of the schistose facies of the gabbro. Evidently this pegmatite, which developed as an early satellitic facies of the gabbro magma, was more or less broken up and involved with the yet molten gabbro.

Two miles southeast of Chestertown a gabbro stock with highly foliated facies not only contains inclusions of, but also sends dikes into, the granite porphyry country rock. At its north end the foliation of the gabbro perfectly conforms to the rather irregular side of a large mass of pegmatite, which latter is cut by well-foliated, fine-grained gabbro in the form of dikes up to eight feet long, one of these dikes ending in a feldspar-biotite schist. A dike of similar fine-grained gabbro not over six inches wide cuts the granite for thirty feet. In this case it seems certain that the pegmatite must have formed well before the solidification of the parent gabbro, because the pegmatite was intruded by the molten gabbro.

At the top of Hackensack Mountain near Warrensburg a dike of the gabbro clearly cuts syenite, and the fluxion structure of the gabbro conforms to the borders of a small mass of included pegmatite.

Conclusions regarding pegmatites associated with gabbro.—From many occurrences like the examples above described it is concluded that acidic masses ranging from pegmatite rich in potash feldspar and quartz, with or without tourmaline, to pegmatite which is mostly potash feldspar, to pegmatite rich in acidic plagioclase with or without quartz, to basic pegmatite which consists either of basic plagioclase and hornblende or nearly all basic plagioclase, to aplite dikes, and even to nearly pure silica (silexite), developed as satellites of the stocks of normal gabbro. It is also concluded that the development of pegmatite began while the gabbro was still notably fluid, and that it continued until it had almost or completely solidified. Accordingly it seems necessary to regard the earlier-formed pegmatite masses to have developed as segregation masses rather than as true dikes.

It is possible, as maintained by Grout[1] for the Duluth gabbro, that some development of pegmatite may have taken place before the beginning of crystallization of the gabbro magma, but the evidence in the North Creek district is not conclusive. Many of the North Creek pegmatites differ from the Duluth pegmatites in one important respect, namely, that they developed as satellites of the gabbro late in the stages of magma consolidation, some of them probably even after complete solidification.

Such a profuse development of so many kinds of pegmatites from gabbro bodies is not in agreement with the commonly held view as stated by Weinschenk, who says that pegmatites "are relatively rare with plagioclase rocks," and "the more basic the plutonic rock, the simpler are its satellites."[2]

Grout's work on the origin of the pegmatites of the Duluth gabbro and the writer's work on the origin of the pegmatites of the granites of the Lyon Mountain district and of the gabbro of the North Creek district clearly show that many of the pegmatites of those districts are not, as is so commonly stated for other regions, to be regarded as intrusions into already solidified portions of the magma from which they were derived.

[1] F. F. Grout, *Econ. Geol.*, XIII (1918), 190–92.

[2] E. Weinschenk-Johannsen, *Fundamental Principles* (1916), p. 142.

WAS THERE A "CORDILLERAN GLACIER" IN BRITISH COLUMBIA?

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In August, 1888, the late Dr. G. M. Dawson, then assistant director of the Geological Survey of Canada, published in the *Geological Magazine* a paper entitled "Recent Observations on the Glaciation of British Columbia and Adjacent Regions," in which he states that

the examination of this northern region may now be considered to have established that the main gathering-ground or *névé* of the great Cordilleran Glacier of the west coast, was included between the fifty-fifth and fifty-ninth parallels of latitude in a region which, so far as explored, has proved to be of an exceptionally mountainous character. It would further appear that this great glacier extended, between the Coast Range and the Rocky Mountains, southeastward nearly to latitude 48°, and northwestward to latitude 63°, or beyond, while sending also smaller streams to the Pacific Coast.

In a subsequent paper[1] published in the *American Geologist* for September, 1890, he writes of his conclusions derived from his geological explorations in British Columbia as follows:

Having thus surrounded the area of this great glacier, it was proposed to name it the *Cordilleran Glacier* in order to distinguish it from the second and larger ice-cap by which the northeastern part of the continent was at the same period more or less completely covered.

The Cordilleran Glacier, as thus defined, had, when at its maximum development, a length of nearly 1,200 miles. The main gathering-ground or *névé* of the *mer de glace* was contained approximately between the fifty-fifth and fifty-ninth parallels of north latitude, that part of the ice which flowed northwestward having a length beyond these limits of 350 miles, that which flowed in the opposite direction a length of about 600 miles.

In another place in the same paper he says:

The width of this (Cordilleran) zone is about 400 miles, and on one side of it lies the wide area of the Great Plains, on the other the Pacific

[1] "On the Glaciation of the Northern Part of the Cordillera," by George M. Dawson, *Am. Geol.*, September, 1890, pp. 153–62.

Ocean. . . . . This part of the Cordillera of the West was, in the Glacial period, covered by a great confluent glacier-mass.

In a longer paper, published in the same year in the *Transactions of the Royal Society of Canada* (Vol. 8, Sec. 4, pp. 3–74), he reiterated his belief in this glacier, and gave a map showing its extent from the Yukon Territory down to an irregular line south of latitude 49°.

Last summer my mining duties called me to British Columbia and I traveled by the Grand Trunk Pacific Railway, stopping off at Prince George, which is on the interior plateau of the province, just south of latitude 54° north, and 80 or 90 miles in a direct line southwest of the eastern range of the Rocky Mountains. Its elevation is 1,862 feet above sea-level. From Prince George I descended the Fraser River, a distance of about 70 miles in a straight line, to Quesnel, which lies at an elevation of 1,570 feet above sea-level, and from there went eastward 50 miles to the old gold-mining district of Cariboo, which is at an elevation of about 4,000 feet above sea-level. During this time I was in the middle of the region of which Dr. Dawson writes "that the ice reached a general thickness of 2,000 to 3,000 feet above even the higher tracts of the plateau, while it must have attained a thickness of over 6,000 feet above the main river valleys and other principal depressions of the surface."[1] It was therefore natural for me to look for evidence of intense ice action such as may be seen in valleys cutting through or descending from the Coast Range of this western province, but such evidence was conspicuously absent.

The Fraser River flows in a direction a little east of south in the bottom of a great wide valley, with high rugged mountains in the distance both to the east and west, this valley being simply the lowest part of the great interior plateau of British Columbia.

On the eastern side of this valley or plateau, and on the western slopes of the mountains which define its eastern rim, is the Cariboo district in which marvelously rich placer mines were discovered and worked in the early sixties of last century. The rocks composing the mountains are pre-Cambrian or Cambrian sericitic and chloritic schists. Deep, narrow valleys carry streams

[1] *Am. Geol.*, September, 1890, p. 155.

down from the sides of these mountains, and gold was found in gravel, and in bedrock beneath the gravel, in the bottom of these valleys. Much of the gold occurred in preglacial, or Pliocene, gravels that had been buried under a bed of massive bowlder clay, holding many glaciated pebbles and bowlders. Immediately under the bowlder clay is often a stratified deposit of fine quicksand or slimy silt, locally known as "slum," which is a sericitic silt that was washed from the decomposed surface of the rock by glacial streams before the advancing glaciers themselves had reached so far down the valleys.

It was in the latter part of the month of May, and snow still covered the tops of the ridges when I was in the district. Though I saw many rock exposures, but one, a quartz vein, had preserved glacial grooves and striae. This vein was on the north side of the valley of Lightning Creek, one of the principal streams of the district, and 1,000 feet above the bottom of the valley, or 4,800 feet above the sea. The markings ran N. 45° W. (true), which was roughly parallel to the course of the valley, and the direction of motion of the ice was quite clearly indicated by some rock cliffs in the vicinity.

As Lightning Creek Glacier moved down the valley it removed loose material from the lateral slopes and deposited some of it in the tributary gulches, thus covering the bottoms and the upper sides of these gulches. After the glacier had retired and disappeared, the drainage of the country was re-established in the same gulches as before, but on top of the bowlder clay left by the glacier and farther down the stream, so that when the gold miners wanted to find the deeper preglacial channels of the gulches they were obliged to explore for them in an easterly direction or up the main stream. In the valleys of Slough Creek and Willow River similar conditions prevail with regard to the lateral gulches, as doubtless local valley glaciers also moved westward and northwestward down these valleys.

Well-marked moraines are present in many of the valleys, conspicuous among them being a large hilly moraine in the valley of Slough Creek below Jack-of-Clubs Lake, and a similar lumpy, pitted moraine in Lightning Creek Valley below Stanley.

Hydraulic operations have exposed excellent sections of bowlder clay in a number of places, and there is only one bowlder clay, namely that of the valley glaciers. I am quite satisfied that the only glaciation that has ever prevailed in this country was the local glaciation from the adjoining mountains.

After spending a few days in the district we returned westward along the wagon road to Quesnel. This road follows the bottom of the valley of Lightning Creek Valley for 15 miles or more, then crosses a sand and gravel plain, after which it descends into the valley of Cottonwood River. In this distance very little rock is exposed, and there is but little evidence of glaciation, except one or two local moraines. On Cottonwood River, near the bridge, basic igneous rocks occur, probably cutting the Oligocene conglomerates, but I was unable to find any evidence of glaciation on them.

Five or six miles farther west the road crosses a lumpy moraine dotted with small lakes, and a short distance farther west it skirts a low rounded hill of porphyritic red granite, the surface of which shows strong glacial markings running N. 15° W., the direction being clearly indicated by the rounded stoss and broken lee sides of the knolls. As seen from this hill the view to the southward is up the wide valley of the Quesnel River, and it is evident that the glacier which formed the markings on the rock descended this valley. The moraine just crossed was also doubtless formed by the same glacier. Though a careful examination was made of the exposed rock no scoring or polishing, other than that caused by the one glacier, could be found. From this rocky hill, which is at an elevation of 3,200 feet above the sea, our course was westward for about 14 miles to the village of Quesnel on the east bank of Fraser River. Throughout this distance no rock was seen, the surface being mostly composed of sand and gravel arranged in wide terraces, though bowlder clay was occasionally recognized.

Fraser River itself, between Prince George and Quesnel, is a large stream which has cut out a winding, gorgelike valley. Above Quesnel as far as Cottonwood Canyon the banks are steep, often almost vertical, and are composed of horizontally stratified conglomerate and soft sandstones of Miocene(?) age.

As seen from the river the banks rise to a horizontal plain, which extends eastward and westward for an indefinite distance. Here and there as many as five different terraces might be counted one above the other on the insides of some of the bends, but altogether the valley has a very juvenile appearance. It is clearly preglacial, for bowlder clay may be seen resting on its sloping sides and lying on some of its terraces. In some places, where it has been partly filled by bowlder clay during the glacial period, the channel has been re-excavated to about its previous depth. Near the top of its banks beds of bowlder clay are here and there interstratified with layers of sand, some of which have been crumpled, giving evidence that glaciers from the mountains to the east or west descended into lakes which then existed in the bottom of the valley, and squeezed up the beds of gravel and sand that had just been deposited in those lakes.

Above Cottonwood Canyon the valley maintains the same general character as below it, with steep banks rising to the adjoining plain, but in addition to the Miocene(?) conglomerates, etc., schistose rocks, similar to the Cariboo schists, outcrop here and there, while at still other places the banks are composed of stratified sand or clay of glacial or postglacial age.

It is impossible to imagine such a winding, gorgelike valley as this of the Fraser River, with its short curves, and with the relatively sharp angles where its steep sides meet the surrounding plain, continuing to exist after a great continental glacier many thousands of feet in thickness has passed along it. Its appearance is quite different from that of such of the British Columbia valleys as have undoubtedly been occupied by great glaciers. On the contrary it has a strong topographic resemblance to the Yukon Valley near Dawson City, where the river flows through an unglaciated part of the Yukon Plateau, which is a northern continuation of the interior plateau of British Columbia. Here glaciers formerly descended from the Coast Range of mountains eastward to the interior plateau, and others descended from the Rocky Mountain range westward to the same plateau, but as they did not meet they left an unglaciated area between them. In the Fraser Valley glaciers also descended from the mountains to the east

and to the west, toward the middle line of the intermediate plateau or valley. For the most part they ended before they reached the present river channel, but in other cases they discharged into great lakes, in which the white silts which form such conspicuous cliffs near Prince George were deposited.

The glaciers always moved inward from the mountains which form the sides of the valley toward its median line, and the ice was thicker on the mountains than in the valley. At no time was this portion of the interior plateau covered by a glacier of the extent and thickness indicated by Dr. Dawson, namely 6,000 feet deep over the lower land, from which the ice moved outward in all directions.

This conclusion is in accord with the observations of the late G. S. Malloch, of the Geological Survey of Canada, who, in 1909, made a geological examination of the upper part of the Fraser River from Tête Jaune Cache down to Prince George. He states that

> bowlder clay occurs at different points along the river. These deposits were formed by two sets of glaciers, the first of which descended into the Interior Plateau from the mountains to the east, and the second from those to the west. The drift of the latter is characterized by the presence of granite fragments from the Coast Range, and volcanic rocks from the western part of the plateau. On the other hand, that from the east contains fragments of older rocks, and it alone is seen on the river from Tête Jaune Cache to Giscome Rapids, where it is overcapped by the drift from the west.[1]

These observations therefore exclude the possibility of the existence of a great longitudinally moving Cordilleran Glacier on this portion of the interior plateau in latitude 54°, and my own observations show that it was absent as far south as Quesnel in latitude 53°. From there to the southern end of the glacier as defined by Dr. Dawson is only a little more than 300 miles, and even if the whole of the country throughout this distance were covered by ice it would not fulfil the idea of a great continental glacier. As to what were the ice conditions north of Prince George, between latitude 54° and 63°, we have not yet sufficient information available to enable us to decide.

[1] *Geol. Surv. Can. Sum. Rep. for 1909*, Ottawa Govt., 1910, p. 128.

Reviews

Geology and Mineral Resources of Kenai Peninsula, Alaska. By G. C. Martin, B. L. Johnson, and U. S. Grant. U.S. Geol. Surv., Bull. 587, 1915. Pp. 243, pls. 38, figs. 43.

This volume is a summary of what is known of the geology and mineral resources of the Kenai Peninsula, including both the results of the early investigations and the hitherto unpublished work of the present writers. In an introductory chapter Martin summarizes the geology of the general region; the succeeding chapters are devoted to a more detailed discussion of its several parts. The relations of highly folded pre-Tertiary sediments and associated lavas and intrusives of the Kenai Mountains are as yet imperfectly known. Rocks definitely assignable to the Triassic and to the Jurassic are known over limited areas, but the great bulk of the slate and graywacke series has not been differentiated. It may include upper Paleozoics and possibly some Mesozoics younger than the Jurassic. The Sunrise group of earlier writers probably represents the upper part of this series and seems to be more nearly equivalent to the Orca group than to the Valdez group in the Prince William Sound region. The only Tertiary beds of the Kenai Peninsula are those of the non-marine Kenai formation.

The gold lodes of the northern Kenai Peninsula are described by B. L. Johnson. The deposits are of three general types—fissure veins, stringer lodes, and mineralized silicic dikes. The veins occur in two distinct sets, standing approximately at right angles to each other and dipping at high angles. Both sets of fractures are ore-bearing and of about the same age. Their average thickness is between 2 and $2\frac{1}{2}$ feet. The present known vertical range of these veins is about 5,000 feet. Of minor importance are the stringer lodes, characteristically developed in the slates and graywackes parallel to the cleavage and bedding planes. Only slightly mineralized dikes have been discovered thus far. The mineralogical composition of the veins is simple and indicates deep-seated conditions of origin. Quartz is the predominant gangue mineral, Calcite is generally present and albite locally. Arsenopyrite, galena, sphalerite, and pyrite are the characteristic sulphides, arsenopyrite being most abundant. Chalcopyrite and pyrrhotite are less common.

Molybdenite is present at two localities. The gold occurs in the native state. The mineralization was subsequent to the intrusion of the Mesozoic granite batholiths and the related stocks and dikes. The depositing solutions were probably residual emanations from these magmas. The gold lodes of the Kenai Peninsula correspond, therefore, both in age and general association, with the similar deposits elsewhere in Alaska.

H. R. B.

Field Geology. By FREDERIC H. LAHEE. New York: McGraw-Hill Book Co. 12 mo, pp. xxiv+508. $3.00.

This work is divisible into two parts: an empirical treatment of geologic phenomena (twelve chapters), and a compilation of field and office methods (six chapters).

The first part covers well-nigh the whole field of phenomenal geology and will find its greatest usefulness among undergraduate students. For working geologists the most valuable matter will be found in the chapters on "Geologic Surveying," "Modes of Geologic Illustration," "Geologic Computations," and "Preparation of Geologic Reports," and in appended tables. One wishes that more of the field and office methods contributed in the last few years to economic geology were presented.

In carrying out the scheme of empirical treatment of phenomena the author has constructed many carefully analyzed "keys" or tables, like those of mineralogical and botanical texts. The reviewer has tried out the work in two field courses, placing it in the hands of the students simply as a reference, and has found it very valuable, though the students did not voluntarily make use of the "keys." These may find their usefulness among beginners without field association with more experienced men.

The author has digested pertinent matter from such works as Leith, *Structural Geology;* Leith and Mead, *Metamorphic Geology;* Grabau, *Stratigraphy;* Lindgren, *Mineral Deposits,* etc., and presents valuable material from the field handbooks of Hayes, of Farrell, and of Geikie. Important contributions to periodical literature have also been drawn upon.

The book is one of the McGraw-Hill series of limp-cover handbooks, with narrow margins and rounded page corners. Its 500 pages of thin paper will prove no burden in the pocket.

J. H. B.

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VOLUME XXVII NUMBER 2

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

FEBRUARY-MARCH 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, LONDON AND EDINBURGH
THE MARUZEN-KABUSHIKI-KAISHA, TOKYO, OSAKA, KYOTO, FUKUOKA, SENDAI
THE MISSION BOOK COMPANY, SHANGHAI

February-March 1919 Vol. XXVII, No. 2

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Separates, if desired, must be ordered in advance of publication. Separates of leading articles will be printed as ordered, of which 50 (without covers) will be furnished *gratis*, the actual cost of the remainder (and covers, if desired) to be paid for by the author. The actual cost may vary, and will depend upon the amount of work in remaking the pages into forms, presswork, paper, binding, etc. Separates containing half-tones may be expected to cost somewhat more, the increase depending upon the number of cuts and the amount of work required upon them.

Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

VOLUME XXVII NUMBER 2

THE

JOURNAL OF GEOLOGY

FEBRUARY-MARCH 1919

SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE PRE-CAMBRIAN OF NORTHERN QUEBEC[1]

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PART I

INTRODUCTION

In the present paper the writer will describe briefly the known geology of that part of northern Quebec whose four corners are the north end of Lake Timiskaming, James Bay, Lake Mistassini, and Lake St. John, with the particular object of setting forth the stratigraphic sequence and age relations of its ancient volcanic and sedimentary rocks.

This region is of especial interest on account of its development of rocks of early pre-Cambrian age. The relations existing between these rocks are shown very fully and satisfactorily, and their examination enlarges our knowledge of pre-Cambrian history and introduces corresponding changes in nomenclature. Structural work in this region, as described in this paper, demonstrates (1) a uniform sequence of extrusion in the lavas, termed the Abitibi

[1] Published by permission of the Geological Survey of Canada.

volcanics, which form the basal rocks of the region; (2) the existence of a thick sedimentary series, the Nemenjish series, which lies, so far as results at hand indicate, conformably on the surface of the lavas, and which appears to correspond to the Grenville series; (3) the occurrence of a second sedimentary series, the Mattagami series, in scattered patches unconformably on the surface of the older lavas and sediments. All of the rocks mentioned are older than the Cobalt series of the Timiskaming district, and are probably of pre-Huronian age, using the term "Huronian" as defined by the International Committee. The basal series of lavas may be of the same age as the Keewatin of the south shore of Lake Superior. The younger series of sediments (Mattagami) appears to occupy a new position in the geologic column, hitherto unfilled, between the Keewatin and the Lower Huronian of the International Committee's classification.

The region approximates in shape a rectangle 270 miles from north to south, and 350 miles from east to west (Fig. 1). Since 1908, the western third of it has been studied in considerable detail by M. E. Wilson, J. A. Bancroft, and T. L. Tanton; the greater part of the remainder has been rapidly examined by reconnaissance methods by the writer. In addition, the Chibougamau Mining Commission has examined a limited area around Lake Chibougamau in detail, and J. A. Dresser has similarly studied an area around the south end of Lake St. John. The northern Quebec region connects on the southwest with the Cobalt-Sudbury-Lake Huron region, which has been mapped in detail by Miller and Knight and W. H. Collins, so that a correlation of the whole Lake Huron-Cobalt-northern Quebec region presumably may be attempted in the near future.

This paper is merely a preliminary attempt to piece together some of the fragments of the pre-Cambrian record. The reader should remember the difficulties of deciphering this record, since the areas of ancient rocks are frequently small and disconnected, and the rocks themselves have commonly been sheared and recrystallized. As work is carried over larger areas and the number of facts for piecing out the record becomes greater, many of the conclusions stated in this paper will undoubtedly be modified or discarded. The writer considers, however, that such a concrete

generalized conception as he endeavors to present is of value, even if not wholly correct. In the words of Van Hise:[1] "The attempt to give a generalization . . . . sharpens the wits and makes the geologist think of relations which were not before observed. . . . .

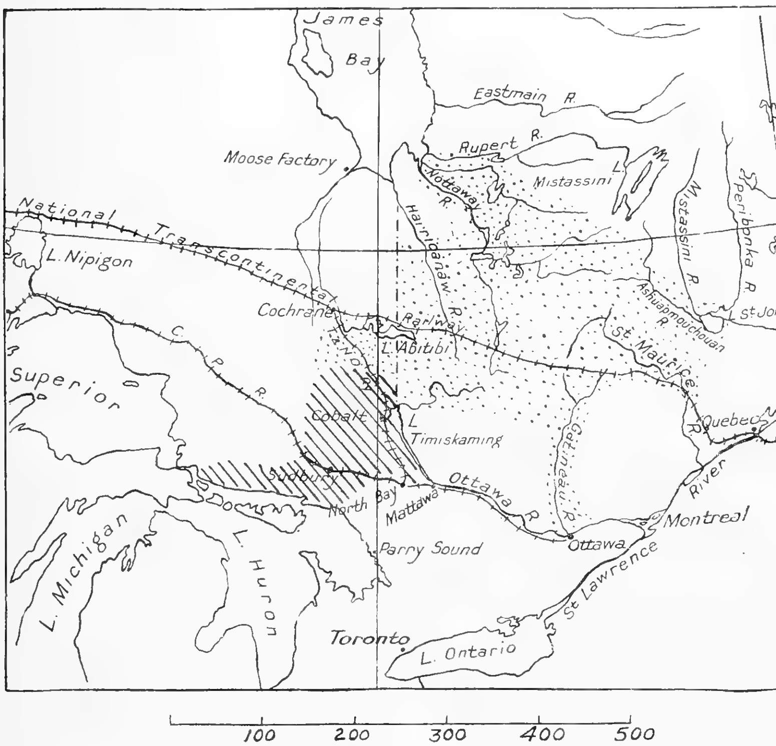

FIG. 1. Work done since 1908 in northern Ontario and Quebec. Dotted areas covered by reconnaissance methods; hatched area, by detailed methods.

He has an hypothesis or hypotheses which he is either to verify or disprove, and consequently will work with greater keenness and insight."

PREVIOUS WORK AND CORRELATION

The northern Quebec region has long been known, and a considerable amount of geographic and geologic work has been done in it

[1] Van Hise, "Principles of North American Pre-Cambrian Geology," *U.S. Geol. Surv., Ann. Rept.*, XVI, 742.

by the earlier explorers, Richardson, Bell, Low, McOuat, and others. The results of this work, which was all of a reconnaissance nature, were published by the Geological Survey of Canada in 1903 as a map entitled "A Geological Map of the Basin of the Nottaway River," on a scale of ten miles to one inch. On this map, which has been out of print for some years, the rocks were subdivided into "Laurentian" and "Huronian." The former group included gneisses, granites, diorites and diabases; the latter schists, arkose, quartzite, etc.

The work done by M. E. Wilson, J. A. Bancroft, T. L. Tanton, and the writer has since the issue of the above-mentioned map resulted in a more precise mapping of the rocks of the region according to their age relations. These geologists have refrained from attempting the correlation of the formations described by them with formations outside the limits of the region and have used local names. It follows that there is at present no literature dealing with the correlation of this area with others. This paper is the first to deal with this problem, which is of a twofold nature. The first part, which can be dealt with with some degree of certainty, is the correlation of patches of formations of similar relationships within the region itself; the second part, on which the evidence is much more scanty, is the problem of correlating these formations with others beyond the limits of the region. In the latter regard there is some recent literature that has a direct bearing on the problems of this region.

The age relations of the Cobalt series of sediments have been recently established by W. H. Collins. He has traced these sediments from the Cobalt district to the original Huronian area on the north shore of Lake Huron and shown that there they overlie unconformably the Bruce series, which appears to be identical with the Lower Huronian of the Marquette district. As a tongue of the Cobalt series projects into the southwest corner of the northern Quebec area, where it overlies the older rocks with great unconformity, this determination of Collins is of the utmost importance in fixing the age of these older rocks.

Certain ancient sediments in Ontario have been described in recent years by Coleman, Miller, Collins, and others, under the local

names of Subdury series, Timiskaming series, and Hastings series. These may eventually be correlated, altogether or in part, with the Mattagami series of the region under discussion; but lack of knowledge makes this as yet no more than an interesting possibility.

The basal lavas of this region and of the Timiskaming district have almost universally been termed "Keewatin" by various writers, but there is little good evidence for so correlating them. Like the Keewatin of Lake Superior, they occupy a basal position in the geologic column, appear to be of pre-Huronian age, and are prevailingly basaltic and andesitic in composition; but more precise evidence of identity is lacking.

In connection with the occurrence in the northern Quebec region of a series of sediments which appear to be of Grenville age, a brief statement of the present status of the Grenville series is necessary. Rocks of the Grenville series were first described by Logan in 1847, and since that time he and many other workers have studied the series and extended our knowledge of it. A summary of the different investigations is given in Van Hise and Leith's "Pre-Cambrian Geology of North America."[1] The series has been definitely recognized only in eastern Ontario, Quebec, the Adirondacks, and the little-known area of Baffin Land; and singularly enough, in these areas other surficial formations of the pre-Cambrian are lacking, excepting the comparatively small development of the Hastings series, together with certain basic lavas. It was therefore impossible definitely to correlate the Grenville with any part of the pre-Cambrian developed in the region of the Great Lakes. Recognizing this, the International Committee in 1907 adopted the following simple succession for this region:

Cambrian: Potsdam sandstone, etc.
  Unconformity
Pre-Cambrian: Grenville series
  Intrusive contact
Laurentian

In the same year Miller and Knight, of the Ontario Bureau of Mines, published a brief description of work done by them in the

[1] *U.S. Geol. Surv., Bull. No. 360*, p. 448.

vicinity of Madoc, Ontario, contributory to the problem of correlation.[1] In this paper they state that in this district "an old greenstone series, with associated acidic, igneous rocks, similar to the Keewatin of the Lake Superior region, is widely developed. . . . . It has been proved by the writer that the Keewatin here is the oldest series in the region. The limestones are found to have been deposited on the surface of the Keewatin. An ancient Keewatin lava has, in places, been subjected to little denudation before the deposition of the Grenville limestone, which fills the cracks and openings in the ropy surface of the lava." This evidence, though interesting, is scarcely convincing, principally because it assumes that the basic lava apparently underlying the limestone is correlative with the Keewatin lavas of Lake Superior region. As basic lavas are found in the Lake Superior region, not only in the Keewatin, but throughout the whole pre-Cambrian, such an assumption cannot be accepted without proof. Exception might also be taken to the validity of the evidence advanced in regard to the relative ages of the lavas and the limestones. These rocks are all tilted into vertical attitudes; so that calcite might easily be carried by meteoric water from the limestone and deposited in cracks in the lava, even though such cracks were not formed till long after the folding was completed. Again, such cracks might have formed during the folding, and the limestone have flowed into them under the pressure of deforming forces. Either of these hypotheses would explain the presence of limestone in the cracks in the lava near the contact, regardless of whether the limestone had lain above or below the lava before deformation took place.

In 1914 Miller and Knight published a more extensive paper[2] on the relationships of the rocks of eastern Ontario. In this paper they still maintain the conformable relationships of the Grenville to the "Keewatin," but without adducing much new evidence. They describe in the Actinolite-Cloyne area a nuclear mass of greenstone surrounded by Grenville sediments. Regarding the relationships of the two, they state: "In the first place it is clear that the greenstone is not a deep-seated intrusive, or batholith,

[1] *Rept. Ont. Bur. of Mines*, 1907, Part 1, p. 221.

[2] *Ibid.*, 1914, p. 2.

invading the Grenville sediments. It is a volcanic or surface rock, retaining in places an ellipsoidal or pillow structure, and a fine or medium-grained texture. In the second place the greenstone does not send dykes into the sediments, nor give other evidence of being intrusive into these rocks. It is thus *inferred* that the quartzite, greywacke, and limestone are younger than the pillow lavas." Basing upon this evidence their conclusion that the "Keewatin" is older than the Grenville, they determine the Grenville to consist, from the base up, of gray gneisses and quartzites, some of which are garnetiferous, iron formation, and crystalline limestones.

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GENERAL GEOLOGY

The oldest rocks of the district are lavas, tuffs, and sediments. The bulk of the lavas are basalts and andesites, but more acid types, such as rhyolite porphyrites, are also present, though only in relatively small amount. Like the flows the tuffs vary in composition, and are of both coarse and fine grain. The flows and tuffs have been locally metamorphosed by dynamic or thermal agencies. They are probably to be correlated with the so-called "Keewatin" of Timiskaming district to the southwest; that they are of the same age as the Keewatin of the Lake Superior district has not yet been established.

The sediments associated with the volcanics are all more or less recrystallized and are now chiefly represented by garnetiferous and non-garnetiferous biotite gneisses, garnetiferous and non-garnetiferous hornblende gneisses, and crystalline limestones. These rocks probably are the metamorphic equivalents of impure sandstones, shales, and limestones. The original nature of the hornblende gneisses is not fully established, but from the entire absence of any evidence of igneous origin they are tentatively assumed to have been sediments. The clastic beds grade downward into beds of more tuffaceous composition, which lie conformably on the surface of the lavas. Evidence has been obtained that seems to indicate that these sediments, which have been termed the Nemenjish series, form the northern equivalent of the Grenville series of eastern Ontario and the Adirondacks.

In the vicinity of Lake St. John a granite is reported by J. A. Dresser to intrude the Grenville series and to be cut in turn by anorthosite. This granite has not been definitely shown to occur anywhere else throughout the region under discussion, but the reports of Adams, Cushing, and others suggest that it is found in areas to the east and south.

Younger than the granite just mentioned, and intrusive into it and the Grenville series, are great bodies of anorthosite and gabbro. Several of these are found in the area under discussion.

A few small patches of a younger sedimentary formation are found here and there throughout the region. These have hitherto been known by various local names, such as the Pontiac, Mattagami, and Broadback series. They include mainly conglomerate, arkose, and greywacke, and lie unconformably on all the older rocks, with the possible exception of the anorthosites. They are highly folded and metamorphosed, so that even the most competent of the rocks are converted into schists.

Following the deposition of these sediments came an intrusion of lamprophyre dykes. They are relatively few in number, but their distribution appears fairly general. Next in age are the enormous batholithic intrusions of granite, which now underlie about one-half of the region. It is possible that these may be of different ages, but no evidence of this has as yet been found. The intrusion of the batholiths probably followed closely the orogenic movements which folded the older rocks. They seem to have removed by stoping and digestion enormous thicknesses of the older rocks, including all of the ancient floor on which these were laid down, and undoubtedly also had a certain metamorphosing action on the adjacent rocks.

The Cobalt series, of Huronian age, rests with great unconformity on the surface of the complex described above. It is definitely recognized only in the southwest corner of the region, but a few small areas of similar rocks occur on Chibougamau Lake, and in the report of the Chibougamau Mining Commission were correlated with the Cobalt series.

Dykes of diabase petrographically similar to the Cobalt diabase cut the Cobalt series and all the older rocks. They are found sparsely distributed throughout the entire region. The diabase here never forms sills as in the flat-bedded rocks of the Cobalt region; hence the chance of mineralization by it is slight.

The youngest consolidated formation in the area is supposedly the flat-lying Mistassini limestone, which outcrops around Lake Mistassini and has been described by A. P. Low and the Chibouga-

mau Mining Commission. Because of its undeformed character and the presence of indistinct fossil-like forms, this formation has been placed tentatively in the late pre-Cambrian or early Paleozoic.

The geological succession, therefore, is as follows:

Mistassini limestones
    Unconformity?
Diabase dykes
Cobalt series (includes Chibougamau formation?)
    Great unconformity
Granite
    Intrusive contact
Lamprophyre dykes
    Intrusive contact
Sedimentary series (Pontiac series, Mattagami series, etc.)
    Unconformity
Gabbro and anorthosite
    Intrusive contact
Granite gneiss (around Lake St. John)
Intrusive contact
Nemenjish series
Abitibi volcanics (basalts, andesites, rhyolites)

METHODS OF DETERMINING STRUCTURE IN LAVA FLOWS

The lavas of the region afford exceptional opportunities for structural determination, since they have suffered relatively little deformation beyond a change in attitude. Each flow has moved as a unit during the folding, so that shearing has been confined to a marginal belt from one to ten feet in width. In the remaining portions of the flows the original structures and textures remain largely unchanged and can be used for determining the structure. The lack of deformation is undoubtedly due to the thickness of the flows, which has made them very competent to resist the deforming influences. The latter have been powerful enough to convert the conglomerate, arkose, and greywacke of the overlying Mattagami series into schist.

Grain and pillow or ellipsoidal structure were the structures and textures used in determining the attitude of the flows. Amygdaloidal textures, so frequently useful for the purpose, are not found here, since the margins of the flows are almost invariably schistose.

Pillow structure.—Pillow structure is well developed in the lavas over a large portion of the region, more particularly in the andesitic types, which commonly have large pillows from two to three feet in length. The basaltic lavas for some reason do not seem to form large pillows, the maximum observed being one foot in length; and on account of the blackness of the basalt it is more difficult to recognize and examine the pillows except on unusually clean, wave-washed surfaces.

A section made from top to bottom across an andesite flow about 130 feet thick on Windy Lake showed the following arrangement: At the top there is the usual narrow, schistose zone, below which there is a zone of pillows about 70 feet in width. At the top the pillows are from two to three feet in length; they gradually decrease in size, till near the middle of the flow they attain their minimum length of ten inches to one foot. Here the pillow structure ceases rather abruptly and passes into a fragmental zone about six feet in width. This is a true volcanic breccia, made up of fragments of fine-grained lava up to six inches in diameter imbedded in a matrix of lava of somewhat coarse grain. Some of these fragments are encircled by a whorl of lava about an inch in width, in which flow textures are prominent, as if the fragment had been revolving in the viscous lava. Below the zone of breccia, fine-grained massive lava occurs. The grain of this gradually increases in size as far as the bottom of the flow, where a grain of approximately 1 mm. is attained. This massive, relatively coarse-grained lava was observed in contact with the glassy, ellipsoidal surface of the adjacent underlying flow.

Only one perfect section across the whole width of a thick flow was observed, but a large number of partial sections were obtained, and the data are sufficient to show that the above represents the section wherever the flow is sufficiently thick to possess a massive base as well as a pillowed top. The succession described may therefore be used to indicate the position of the top of a tilted flow, even where only a part of the flow is visible. Of course this method is useless in flows pillowed throughout their entire thickness.

The method of determining the position of the upper surface of the flows from the flattening of the pillows, described by Daly,

Ransome, Russell, and M. E. Wilson, proved so difficult and uncertain of application that it was not used. That flattening is greater on the under side than on the upper was clear in most cases only when the position of the upper side had been previously determined by other means.

Grain.—A progressive increase in grain takes place in passing from the top of the flow toward its base. At the top the lava is

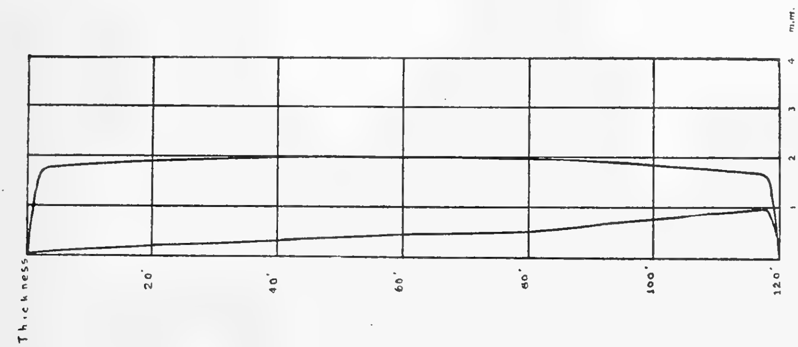

FIG. 2.—The curve to the left shows the change of grain in depth of a non-ellipsoidal andesite flow. The curve to the right is that for an intrusive of the same, thickness and composition. The maximum grain of the latter will of course vary, and may be much larger than represented.

almost or quite glassy, and the grain gradually increases in coarseness with depth till the maximum of approximately 1 mm. (in andesite) is attained a few inches from the bottom, where a narrow chilled edge is found. In the pillow lavas the fine, glassy grain persists throughout the whole thickness of the ellipsoidal zone. The curve in Fig. 2 shows the change in grain with depth of a non-ellipsoidal flow. For comparison the type of curve for an intrusive of the same composition and thickness is introduced.

It is obvious that if a sufficiently wide section can be obtained across the outcrop of a flow to show this change in grain the position of the top will be indicated. This, however, is only occasionally found possible in practice. The method is more applicable to the basaltic flows than the andesites, as their maximum grain is apt to be larger.

The methods of determining the positions of the upper surfaces of the lava flows may be summarized as follows:

A. In a single flow
   1. From changes in pillow structure with depth
   2. From changes of grain with depth

B. At contact of two flows
   1. From observation of a coarse-grained, non-ellipsoidal base resting on an ellipsoidal upper surface
   2. From observation of a coarse-grained base resting on a fine grained upper surface

The latter two methods are much the most useful.

[*To be continued*]

THE SALIENT FEATURES OF THE GEOLOGY OF OREGON.

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INTRODUCTION

No article or book purporting to sum up the known geology of the whole of Oregon has yet been published. Even now the time has not arrived to essay anything like a complete story. Nevertheless it seems to be a propitious time to take an inventory of our knowledge. This seems desirable in that it will give those interested something like a connected account of the salient features, and on the other hand will afford the workers in the field a clearer idea of

the problems involved. The writers are personally acquainted with much of the field and have made up for some of the deficiencies in their own knowledge by drawing upon the literature which they have deemed most reliable. In some cases, as will be indicated in the proper places, they have taken issue with earlier workers.

A few scattered references to the geology of Oregon in the earliest reports of various kinds are mainly of historic interest, but naturally at that time could not throw much light on problems of Oregon geology.

Dr. Thomas Condon, formerly a missionary, who came to Oregon in 1852, and who because of an unquenchable love and aptitude for natural history became a geologist, was the pioneer geologist of this state. His popular book on *Oregon Geology* and his collections, the first to be made in the now famous John Day basin, and the general stimulus he gave to later workers are his contributions, and no one has left a finer legacy to present-day workers.

In his published contributions Dr. Josiah Diller, veteran geologist of the United States Geological Survey, takes the lead. His work began in 1883 and he has since covered most of western Oregon. After Diller comes I. C. Russell, to whom we are indebted for much of our knowledge of southeastern Oregon.

The Oregon Bureau of Mines and Geology, created by legislative act in 1912, has contributed several important results of investigations, more especially relating to the economic aspect of the subject, and this Bureau has given financial assistance to other work which has not appeared in its publications. The Bureau maintains offices and a display collection of ores in Portland and issues monthly *The Mineral Resources of Oregon*.

The chief contribution to our knowledge of the Blue Mountain region of eastern Oregon has been made by Waldemar Lindgren.

Not the least important among the groups of investigators of Oregon geology is the department of paleontology of the University of California, which has devoted its attention largely to the fossil beds of eastern Oregon.

The University of Oregon, represented by a line of workers such as Ellen Condon McCornack, daughter of Dr. Condon, Chester

Washburne, Arthur J. Collier, Graham John Mitchell, and others, has contributed, if not voluminously, most substantially, to the accumulated knowledge in this field.

Besides those mentioned there are several other authors who have contributed one or more papers in special fields, and these are listed in the bibliography, which includes only the more important contributions to the subject.

PHYSIOGRAPHY

The state of Oregon is only a part of the older and much larger Oregon Territory. Its situation on the great western ocean is greatly in its favor, though it is less fortunately placed than either California or Washington.

Oregon is divided by the great Cascade Mountains into two very diverse regions, western and eastern Oregon, which differ radically, at least in the later periods, in physiography (including climate), geology, economic greogaphy, and also politically, socially, and in many other ways. Western Oregon is a marine province, and its geology in part is, in common with California and Washington, similar to that of Eastern Asia, while eastern Oregon is continental and belongs to the Great Basin province. A great portion of Oregon is covered by a part of the greatest lava flow in the world, and this has had a profound influence upon its history, both geologic and economic.

Following the Committee of the Association of American Geographers[1] there have been recognized the following physiographic divisions in Oregon:

1. "*The Oregon Coast Range* is the section of the Pacific Border Province west of the Puget Trough and consisting of Tertiary rocks," sandstones, and shales cut by igneous intrusives.

2. "*The Puget Trough*, the intermontane lowland west of the Middle and Northern Cascade Mountains." In Orgeon this is known as Willamette Valley and is filled largely with alluvium, but many outliers of Tertiary sediments and buttes with Tertiary igneous intrusives are found within this area.

3. "*The Middle Cascade Mountains* are that portion of the Sierra-Cascade Province whose height is due in part to volcanic

[1] *Ann. Assoc. Am. Geographers*, VI, 34.

accumulation and in part to crustal uplift." This is a great dissected plateau. Tertiary sediments in the form of a great synclinorium pass under these Tertiary and Pleistocene lavas.

4. "*The Klamath Mountains* are the section of the Pacific Border Province adjoining the Cascade Mountains on the west and consisting of relatively old and resistant rocks." The most noteworthy feature of this region is the remarkable peneplain described by Diller.

5. "*The Oregon Lake Section* of the Basin-and-Range Province characterized by young block mountains and lake basins."

6. "*The Harney Section* is that section of the Columbia Plateau which lies south of the Blue Mountains." This is largely underlaid by Columbia lava. It is characterized by sage brush, "rim rock," and lacustrine sediments.

7. "*The Payette Section* of the Columbia plateau is the part west of the Snake River Plain, whose substratum consists in large part of lacustrine sediments (applies to northern part only)." This takes in practically all of the upper Snake River drainage.

8. "*The Blue Mountain Section* of the Columbia Plateau Province is the mountainous area entirely surrounded by plateau surface." This section extends up into the northeastern part of the state and includes the Wallowa Mountains, which are in many ways quite different from the Blue Mountains proper. The writers are inclined to make a separate section for this portion.

9. "*The Walla Walla Plateau* is that section which lies north of the Blue Mountains."

This includes most of the DesChutes River basin and that of the famous John Day Valley. This region is noted for its fine wheat lands on the plateau stretches between the rivers and for the classic fossil localities along the John Day.

The writers suggest the following slightly simplified subdivisions:

a) The Columbia-DesChutes Province.
b) The Willamette Valley Province.
c) The Coast Province.
d) The Cascade Plateau Province.
e) The Klamath Province.
f) The Blue-Wallowa Mountain Province.
g) The Southeastern Desert Tract.

a) We think it inadvisable to run a physiographic boundary across a main stream like that of the DesChutes, and suggest that a heavy line (using the scheme of the Committee of American Geographers) instead of a broken line be passed around the *head* of this river. We think Columbia-DesChutes more appropriate than Walla Walla as a name for this province.

b) The writers are not yet ready to subscribe entirely to the inclusion of the Willamette Valley in the Puget Sound Trough and prefer the local name.

c) The Coast Province may be better than Coastal Range, since all of this province is not a mountain range.

d) Cascade Plateau Province we think is more fitting for this dissected plateau than "Cascade Mountains."

f) As the Wallowa, or Eagle Creek, Mountains, as they are sometimes called, are quite distinct in some ways, yet a part of the Blue Mountains, we suggest the name Blue-Wallowa Mountains.

g) We would include all the territory east of the Cascades and south of the Blue Mountains in one physiographic province. This includes territory with nearly similar geology and mainly without exterior drainage. There are differences here, of course, but we think not sufficiently great to warrant such division.

The hydrography of Oregon is interesting. The state is bounded by water on almost the entire distance of three of its sides; on the west by the Pacific Ocean; on the north by the master-stream, the Columbia; on the east for more than one-half the distance by the Snake. The northern and western portions are well drained by the following streams, respectively, the John Day and DesChutes; the Rogue, Umpqua, and Willamette. The major streams in general in Oregon are northward flowing. The southeastern lava plateau and desert region is a part of the Great Basin and therefore practically without exterior drainage.

The lakes of Oregon are especially interesting both for their variety and for their diverse origins. One of these is perhaps the most famous of all the lakes of North America, namely Crater Lake at the summit of the Cascade Mountains. We note the following types, which we can only name in passing in an article of this kind:

1. The coastal lakes—type, Tsiltcoos Lake.
2. The alkali lakes of the southeastern desert region—type, Harney Lake.
3. Crater lakes—type, Crater Lake.
4. Morainal lakes—type, Wallowa Lake.
5. Cirque lakes—type, Aneroid Lake.
6. Fault block depression lakes—type, Warner Lake.
7. Lava flow lakes—many in high Cascades.

STRATIGRAPHY

PRE-CAMBRIAN

Archean.—A biotite gneiss, imbedded in the granodiorite occurring along the headwaters of the north fork of John Day River is thought to be the oldest known rock of Oregon. This metamorphic rock outcrops on the north slope of Bald Mountain, covering an area of less than fifteen square miles. There is no reason given by Lindgren[1] why these rocks are considered as being pre-Cambrian. It is true that they are similar lithologically to gneisses in Calaveras County, California, and those near Shoup and Elk City, Idaho. Since metamorphics are products of dynamic conditions irrespective of time, there is no valid reason why gneisses and schists may not be found in later ages.

Algonkian.—Metamorphic rocks of supposed pre-Cambrian age also occur at or near the California-Oregon boundary. Schists are found near the headwaters of Wagner Creek west of Ashland, at Starling Peak still farther to the west, and thence westward along the boundary line to Takilma, interrupted, however, by smaller masses of Paleozoic metamorphics. These areas, excepting the first mentioned, extend into California in a southeasterly direction for a distance of many miles. These rocks are variously described by Diller,[2] Winchell,[3] and others as amphibolite, hornblendite, hornblende-mica, talc, and mica-quartz schists. Since they are either continuous with, or lithologically similar to, the beds across

[1] *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 594.

[2] J. S. Diller, *U.S. Geol. Surv., Bull. 546*, p. 14.

[3] A. N. Winchell, *Oregon Bureau of Mines and Geol., Vol.* I, No. 5, p. 37.

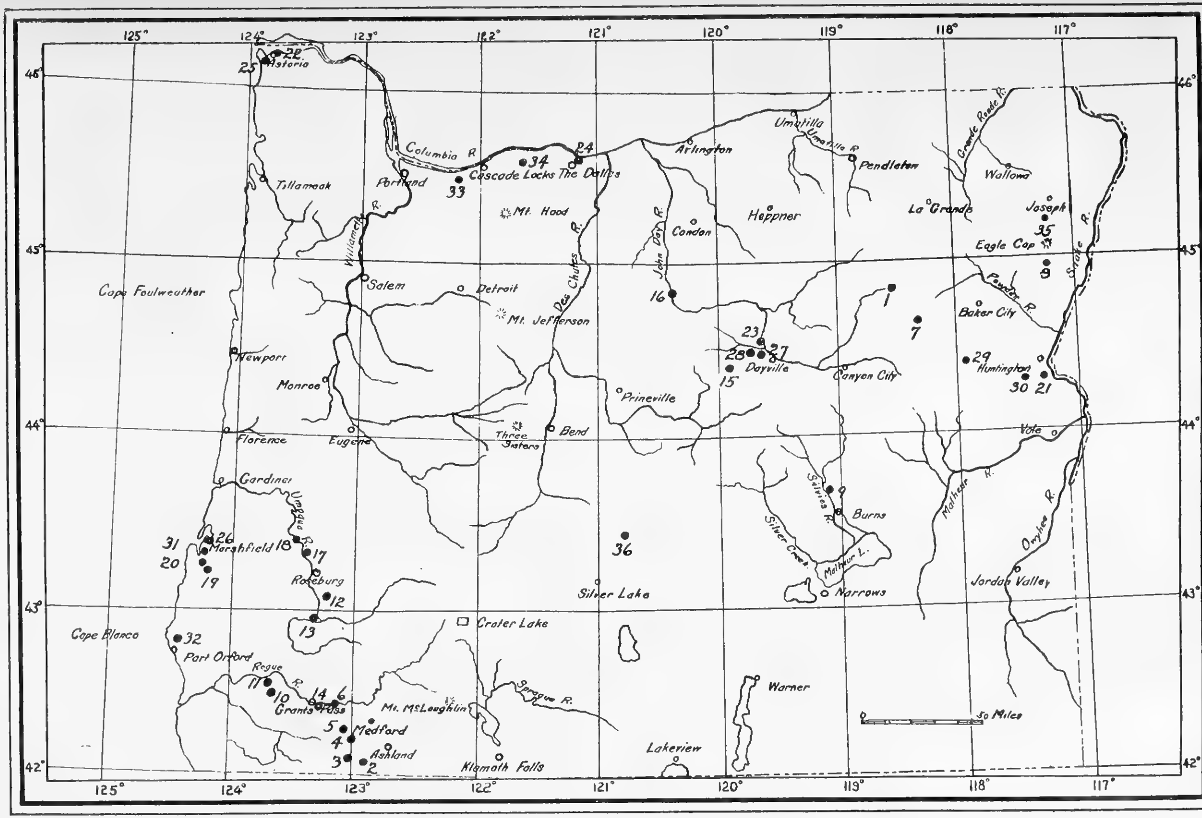


FIG. 1.—Formational locality map of Oregon: (1) Bald Mountain, Archean (?); (2) Abrams, Algonkian; (3) Salmon, Algonkian; (4) Little Applegate River, Devonian; (5) Kane Creek, Devonian; (6) Gold Hill, Carboniferous; (7) Winterville, Carboniferous; (8) Eagle Creek, Triassic; (9) Silvies River, Jurassic; (10) Galice, Jurassic; (11) Dothan, Jurassic; (12) Myrtle, Cretaceous; (13) Riddle Horsetown, Cretaceous; (14) '49 Mine, Chico, Cretaceous; (15) Spanish Gulch, Cretaceous; (16) Clarno Ferry, Eocene; (17) Umpqua River, Eocene; (18) Tyee, Eocene; (19) Pulaski, Eocene; (20) Coaledo, Eocene; (21) Payette, Eocene; (22) Astoria, Oligocene; (23) John Day, Oligocene; (24) Columbia Lava, Miocene; (25) Astoria, Miocene; (26) Empire, Pliocene; (27) Mascall, Miocene; (28) Rattlesnake, Pliocene; (29) Ironside, Pliocene; (30) Idaho Beds, Pliocene; (31) Coos conglomerate, Pliocene; (32) Elk River, Pleistocene; (33) Satsop, Pleistocene; (34) Cascade, Pleistocene; (35) Terminal moraine, Pleistocene; (36) Fossil Lake, Pleistocene.

the California boundary, which have been correlated with Hershey's,[1] Abrams, and Salmon series, it may be permissible to quote the description of the typical facies of those rocks as applicable in general to the Oregon beds:

> It [the Abrams mica schist] is composed of thin folia of muscovite of dull colors . . . . separated by irregular layers of white quartz representing the original laminae. Throughout it is very highly siliceous, and doubtless portions of it would by some be called micaceous quartz schist. In certain belts the silica predominates to such an extent as to cause it to outcrop like great veins of very glassy white and dark blue quartz.

This mica schist in California appears to grade upward through a graphite and actinolite schist to the hornblende schist series. These mica and hornblende schist series have an estimated thickness of 1,000 feet, which is no more than that developed by the first mentioned in the upper Coffee Creek section of northern California.

These old schists are in contact with the tonalite batholith at the California-Oregon boundary south of Ashland. This intrusive is of a much later date and possibly has been the dominant factor in the alteration of these sedimentary rocks to their present condition. Winchell states that these old beds are so intimately associated with intrusives as to make stratigraphic studies impossible in the vicinity of Red Mountain. The schistosity parallels the structure of the adjoining Paleozoic rocks, which have a general northeasterly strike.

Since these rocks, which were presumably originally argillaceous sandstones, or in places carbonaceous, as is testified by the graphitic schists, have been so completely metamorphosed their geologic age must be determined solely upon physical bases. The consensus of opinion seems to be that the schists at the state line are to be correlated with the Abrams and Salmon schist series of supposed Algonkian age.

PALEOZOIC

Devonian-Carboniferous.—During a part at least of the Paleozoic a sea covered a portion of eastern and southwestern Oregon. Although the Paleozoic rocks outcrop in both sections, the forma-

[1] O. Hershey, *Am. Geol.*, XXVII, 227.

tions have not been differentiated, and in both regions the stratigraphy is apparently hopelessly tangled.

In eastern Oregon Lindgren[1] found an argillite series with some limestone, which at Winterville contains crinoid stems, of probable Carboniferous age. Lindgren says of these:

> This argillite series is undoubtedly older than the Trias of the Eagle Creek Mountains, and may without much uncertainty be referred to the Paleozoic, possibly to the Carboniferous, which is so extensively developed in California. The whole argillite series, from Weatherby to the Greenhorn Mountains, is composed of fine-grained sediments, indicating deposition in deep waters. Sandstones, quartzites, and conglomerates are entirely absent, according to present information.

The structural features, according to Lindgren, verified to a limited extent in the field by the senior author, are quite irregular. They strike in the neighborhood of the Elkhorn Range a little north of west and dip 60 degrees south, but in the vicinity of Burnt River and Huntington they dip to the northward and strike southwesterly. No estimate of thickness of these formations, save that it may be several thousand feet, has been made.

In western Oregon there are, according to Diller[2] and Winchell,[3] about 10,000 feet of argillites, tuffs, and sandstones and limestone lenses of marine origin. This is indicated by the presence of siliceous beds containing Radiolaria.

As Winchell[4] has admirably summarized the information regarding these formations, we quote:

> The Paleozoic rocks are apparently structurally conformable both with older formations and with more recent beds, but there seems to be a hiatus in deposition both before and after the period. There is no unconformity known between the formations included in the Paleozoic. Like the Jurassic, the Paleozoic beds are nearly on edge, striking northeast and dipping steeply southeast. Elsewhere in this report the writer has suggested that these beds are all overturned, so that the Carboniferous beds are structurally beneath to the northwest, and the Devonian (and Silurian ?) are above to the southeast.
>
> The classification of these Paleozoic rocks is based on fossils found in the limestone lenses, each of which has a maximum thickness of about 200 feet and a maximum length of about 2,000 feet. They have been assigned to four chief belts.

[1] W. Lindgren, *op. cit.*, II, 578.

[2] J. S. Diller, *op. cit.*, p. 15.

[3] A. N. Winchell, *op. cit.*, p. 35, p. 26.

[4] *Ibid.*, p. 26.

Beginning on the west the first belt includes lenses on Cheney Creek, others near Kerby, and some near Waldo. In this belt fossils collected by the writer have been considered to be probably Carboniferous in age by paleontologists of the U.S. Geological Survey.

The second belt includes outcrops southwest of Gold Hill, also some west of Provolt, those at Oregon Caves, and one on Sucker Creek. So far as known no fossils have been found in this group of outcrops.

The third belt comprises the lime quarries on Kane Creek, the outcrops near Applegate, and those west of Steamboat. Fossils obtained on Kane and Steamboat creeks consist merely of fragments of round crinoid stems.

The fourth belt of lenses is found in several outcrops on Little Applegate River (and across the divide on Anderson and Coleman creeks) and in one (or more) exposures near Watkins on Applegate River. In the former well-preserved round and pentagonal crinoid stems have been found. The fossils do not definitely determine the age of the third and fourth belts, and it seems possible that they should be referred to the Silurian, or an earlier period.

These limestone lenses are of considerable importance because limestone is so scarce in Oregon that the supply for cement and other uses must be sought in them or in similar outcrops. . . . . The origin of the limestone lenses is an unsolved problem of much interest and importance.

MESOZOIC

Triassic.—The Triassic is represented by sedimentaries and associated lavas reported by Lindgren[1] from the southern flank; and by Condon[2] from the northern flank of the Wallowa Mountains in northeastern Oregon. These beds are typically exposed along Hurricane Creek, Eagle Creek, and Powder River. The sedimentary members on Eagle Creek consist of calcareous shales, limestones, and agglomerates, aggregating several thousand feet. Nearer the batholitic core of the range they are altered to slates, schists and marbles. Farther west volcanic rocks, including basalts, andesites, and tuffs, comprise the dominant part of the series, while farther in the Wallowa Mountains masses of greenstone occur which may belong to this series.

J. P. Smith[3] records a section at Martin's Bridge on Eagle Creek consisting of fossiliferous shales and limestones. These are but little deformed. They yielded several species of *Halobia* and a number of corals, including *Montlivaultia* and the cephalopod *Dittmarites*. Condon obtained *Halobia rugosa* Guembel from the

[1] W. Lindgren, *op. cit.*, p. 580. [2] T. Condon, *Oregon Geology*, p. 48.

[3] J. P. Smith, *Am. Jour. of Sci.*, Series 4, XXXIII, 92–96.

north slope of the range, and W. D. Smith[1] notes fossils from near the summit of the range. These faunas are considered by J. P. Smith as representing a portion of the Hosselkus limestone of Karnic and Noric stages of Upper Triassic.

Jurassic.—This system is well developed in southwestern Oregon and is also known from the Blue Mountains. Recognizable Jurassic fossils were obtained by Condon[2] from Beaver Creek, a tributary of Silvies River, and from Red Butte, north of Burns. Nothing has been recorded regarding the extent or geologic relationships of these fossiliferous beds. Hyatt,[3] who examined the Condon collection, describes the matrix as a red sandstone. An examination of the specimens in the Condon Museum shows a fine-grained calcareous matrix, which is presumably an impure limestone.

The fauna includes *Peaten acutiplicatus* Meek, and *Pholadomya nevadana* Gabb as its most representative forms. These place the age of the beds as Lower Jurassic, of the Hargrave stage.

Diller[4] has shown the Jurassic rocks comprise the major portion of Oregon south and west of Rogue River. These rocks consist of sedimentary, metamorphic, and igneous rocks representing a wide range of rock types. The sedimentaries have been designated as the Galice and Dothan formations. Both formations are lithologically similar, and although now separated by a mass of greenstone and a zone of faulting the justification for separation into two formations has been questioned.[5]

The Galice formation outcrops as a band several miles in width extending northeasterly from the Oregon-California boundary. Northwest and roughly paralleling this is the type section some three miles wide and twenty to twenty-five miles long. The Dothan outcrops in a wide band still farther west and possibly extends northeasterly to the vicinity of Roseburg, Douglas County.

Both formations are composed of dark shales and slates, subordinate amounts of conglomerate, and lenses of red or gray chert. Both are steeply tilted, dipping generally to the southeast. The

[1] Smith, W. D. *Mazama*, Series 4, Dec. 1918, p. 238.

[2] C. Washburne, *Jour. Geol.*, IV (1906), 222.

[3] A. Hyatt, *Bull. Geol. Soc. Am.*, V, 401.

[4] J. Diller, *op. cit.*, Fig. 2.

[5] Winchell, *op. cit.*, I, No. 5, p. 35.

discordant dips support Diller's contention of distinct formations. Other field evidence indicates an overturning of these formations, making the Galice the older.

Marine invertebrate fossils from the Galice formation are the basis for the correlation of these beds with the Mariposa Jurassic of California. The fragmentary remains found in the Dothan resemble those from the Galice.

Franciscan Jurassic outcrops along the California-Oregon boundary for a distance of at least ten miles from the ocean shore. This region on the Oregon side, mapped as undifferentiated Jurassic by Diller,[1] undoubtedly contains Franciscan rocks. They also occur farther north in the Roseburg Quadrangle, where certain sedimentary and metamorphic rocks possibly once included within the Myrtle Cretaceous have been called the Dillard[2] and correlated upon their lithologic pecularities directly with the Franciscan. It is not improbable that these rocks connect with the Franciscan eighty-five miles farther south. Subsequent work by W. D. Smith[3] and by Davis[4] confirms the Franciscan age of these beds and adds weight to the prevailing opinion that these rocks are of Jurassic age, and that they are probably either younger or older than the Galice.

Igneous activity was pronounced during the middle Mesozoic. Various batholithic masses were intruded into the sedimentaries of British Columbia and the Coast states, resulting in regional metamorphism and often mineralization of earlier rocks, and either initiating or accompanying the uplift of the Sierras, Klamath, Blue, and Wallowa mountains.

In northeastern Oregon one or more granodiorite batholiths are now exposed as the cores of Wallowa and Blue mountains. Associated with these are diorites, gabbros, and peridotites cutting the pre-Cretaceous rocks of this region. The intrusion of the Siskiyou tonolite batholith was preceded by andesitic extrusives and intrusives, and basic rocks now largely altered to serpentines. These extensive intrusions of quartz diorite were later cut by dacite and aplite dikes. Although it is possible to determine the relative

[1] S. Diller, *op. cit.*, Fig. 2. [2] G. D. Louderback, *Jour. Geol.*, XIII, 528.

[3] W. D. Smith, *Am. Jour. Sci.*, XLII, 299.

[4] E. F. Davis, *Univ. Cal. Publ., Bull. Geol. Dept.*, II, 40.

age of these igneous rocks, their exact geologic age is unknown, they being presumably of late Jurassic age.

Cretaceous.—This system is developed along the southwestern flank of the Blue Mountains, eastern Oregon, and mainly within the valleys of the Rogue, Umpqua, and Coquille rivers of southwestern Oregon. The best-known localities within the former region are Mitchell[1] and the vicinity of Antone in Wheeler County. Broad exposures are found within the Port Orford, Coos Bay, and Roseburg quadrangles, and well-recognized areas in the vicinity of Riddle, Medford, and Ashland.[2]

These rocks in part represent the Shasta-Chico series of California yielding characteristic faunas and being lithologically similar to that series. The Shasta includes the Myrtle of Diller, whose most recent definition would include even the equivalent of the lowermost Knoxville as yet unknown in Oregon.[3]

The lower Myrtle, or the Knoxville of Oregon, as found in the above-named quadrangles, is composed of shales, sandstones, conglomerates, and lenses of limestones, all of which are in places locally metamorphosed and intruded by basic rocks. Dark-blue shales so typical of the Knoxville are known in several lower Myrtle areas in southwestern Oregon as well as at Mitchell in eastern Oregon. This latter locality has not as yet yielded determinable fossils, so its correlation with the Knoxville is only tentative. Heavy Myrtle conglomerates resting upon a basement complex representing successively higher horizons indicate a transgressing sea, which condition apparently continued until the close of the period.

The upper Myrtle, containing a Horsetown fauna, is well developed in the Myrtle Creek syncline of the Roseburg and Riddle quadrangles. It is not known to occur east of the Cascades. These rocks are somewhat more variable lithologically than the Knoxville, probably being more conglomeratic.

The Chico group along Rogue River consists of several thousand feet of sediments formed in a transgressing sea, which perhaps

[1] J. C. Merriam, *Univ. Cal. Publ. Bull. Dept. Geol.*, II, 280.

[2] F. M. Anderson, *Proc. Cal. Acad. Sci.*, Series 3, II, 1–154.

[3] B. Willis, *U.S. Geol. Surv., Prof. Paper No. 71*, p. 618.

extended eastward to the Blue Mountains, where the sediments now comprising the major portion of the Cretaceous outcrops were deposited.

The rocks of the Cretaceous system represent a presumably conformable series, which everywhere lies unconformably upon a complex of older beds. Tertiary strata generally are found to be markedly discordant with the Cretaceous. A long erosion interval appears to have followed the withdrawal of the Chico sea, during which time folding and intrusions occurred, followed by erosion which removed Cretaceous sediment of unknown extent.

The igneous rocks of the Cretaceous include gabbro, basalt, dacite-porphyry, and other rocks now altered to serpentine. These cut the Myrtle group in the order mentioned.

The Knoxville fauna is meager, including the boreal *Aucella piochii* (Gabb) and *A. crassicollis* Keyserling characterizing the lower and upper Knoxville respectively. The tropical Horsetown fauna from Riddle comprises about fifteen species, several of which are known from the California Chico. The Chico of Rogue River valley, at Mitchell, and near Antone in eastern Oregon have yielded a large fauna having local characteristics, yet being closely related to the Upper Cretaceous of California and having strong affinities with the Cretaceous of the Orient.[1] As yet no marine reptiles, so well represented in the interior sea to the eastward, have been discovered in the Pacific Coast province.

Four Pacific Coast Mesozoic floras, known as the Oroville, the Oregon, the Shasta, and the Chico, have been recognized by paleobotanists and have yielded evidence as to the age of certain beds which is difficult to reconcile with that afforded by the marine invertebrates. The oldest of these, the Oroville, is from California and is thought to be Middle Jurassic or pre-Maraposa. The Oregon flora is represented by the Thompson Creek, Douglas County, locality, and consists of over one hundred species, which show close affinities with the Oölite, Middle Jurassic, yet they appear to be associated with Knoxville invertebrates which paleontologists consider as belonging to Lower Cretaceous. The Shasta fauna from Elk River, Jackson County, is certainly associated with a

[1] F. M. Anderson, *op. cit.*, p. 62.

Knoxville fauna, including a number of well-known species. The latest, or Chico, flora is not well represented in Oregon but is in closer agreement with the invertebrate faunas.

CENOZOIC

Eocene.—Marine Eocene is known to comprise parts of the Coast Range[1] of Oregon from Rogue River northward to the Columbia, being well developed along their western flank within the Port Orford and Coos Bay quadrangles, and along their eastern flank within the Roseburg Quadrangle. These sediments outcrop along the western base of the Cascades east of Roseburg and at several localities within the Willamette Valley.

The Eocene rocks consist of sandstones, shales, carbonaceous shales and coals, conglomerates, tuffs, basalts, and various intrusives.

The Umpqua-Arago[2] group, including the marine and estuarine deposits, may represent over 20,000 feet of sediments, which are divided into a number of formations, the exact positions in the geologic column of several of which are as yet uncertain. The oldest, the Umpqua group, is well developed on Little River, Roseburg Quadrangle, where it consists of 7,500 feet of marine sediments. This group includes the Wilbur tuff—lentils, the Umpqua formation, the Tyee sandstone, and possibly the Oakland limestone formations. The most important of these is a rather coarse-grained, thick-bedded sandstone known as the Tyee sandstone. This has been traced by Washburne[3] from Rogue River Mountain northward along the Coast Ranges into Tillamook County.

The Arago, the lower part of which may be the equivalent of a part of the Umpqua formation and the later Tyee sandstone,[4] is found within the coast quadrangles and consists mainly of sandstones and shales, some of which are coal-bearing. The older Pulaski formation also includes some fossiliferous limestone and basaltic tuffs. The younger Coaledo formation is coal-bearing, but along the eastern margin of the field includes some basaltic

[1] S. Diller, *U.S. Geol. Surv., 17th Ann. Rept.*, Part I, p. 469.

[2] *Ibid.*, Folios 49, 73, and 89.

[3] C. W. Washburne, *U.S. Geol. Surv., Bull. 590*, p. 9.

[4] R. E. Dickerson, *Proc. Cal. Acad. Sci.*, Series 4, IV, 114.

flows and diabase. Probable equivalents of the upper portion of this series are found in the Ione lacustrine deposits within the Rogue River valley.

The Eocene beds have been thrown into gentle folds, which even along the crest of the Coast Range are nowhere as steep as those developed in the Myrtle or older beds. In places normal faults have developed, the thrust fault being less frequently seen.

Eocene invertebrates occur at a number of localities. These are typical Tejon forms, including the well-known *Turritella uvasana* Gabb and *Venericardia planicosta merriami* Dickerson. The large fauna from the Little River, Roseburg Quadrangle, as shown by Dickerson, belongs to the Siphonalia sutterenses zone of upper Tejon. Since this was found some 10,000 feet from the base of the Umpqua-Arago series, and since the Arago of Diller has been by several considered later than the Umpqua formation, it may prove to be the brackish water equivalent of the Ione Eocene of California.

With the beginning of the Eocene eastern Oregon became a province, distinct both geologically and physiographically. The oldest Tertiary beds have been described as the Clarno by Merriam,[1] and named after the type locality, Clarno Ferry, Wheeler County. The formation was also recognized in the vicinity of Fossil and along the west side of John Day River, and was later extended eastward to Heppner,[2] as a strip ten to fifteen miles wide.

The Clarno is typically composed of varicolored sandstones and shales, which are in places carboniferous, grading upward into paper shales and coarse rhyolitic tuffs. In places near the bottom andesitic flows are found, while rhyolites occur nearer the top of the section.

These beds range from 400 to 2,000 feet in thickness. They have dips as high as 25 degrees, which may be locally increased upon fault blocks. The Clarno rests unconformably upon Chico Cretaceous at Mitchell and upon the Knoxville (?) shales farther west. An angular unconformity with the overlying John Day beds

[1] J. C. Merriam, *op. cit.*, II, 285.

[2] W. G. Mendenhall, *U.S. Geol. Surv., Bull. 341*, p. 406.

has yet to be reported. It is, however, presumed that a hiatus between the two will be found.

These terrestrial beds have yielded fossil plants only, which were early discovered at Bridge Creek by Condon. The flora, as determined by Knowlton, comprises about twenty-five forms, which indicate the Eocene age of the formation. There is some evidence that both the lower and upper Eocene floras are represented.

In Malheur and Harney counties a series of sedimentary beds occupies, in part, the Snake River Valley from a point near Owyhee northward to Ontario, extending westward to a locality some thirty miles southwest of Vale.

These beds consist mainly of unconsolidated gravels, sands, clays, and volcanic ash. Similar beds along Snake River in Idaho have been described by Lindgren[1] as the Payette formation. He ascribes their origin to a large Neocene lake, but Russell[2] inclined to the belief that the Oregon beds were of fluvatile origin. These may well include other Tertiary strata, as Washburne[3] suggests, and as is apparently proved by Merriam[4] by the discovery of the Ironside formation at Ironside. The fossil leaves and fresh-water mollusks indicate an early Tertiary age for these beds. The Payette has been correlated with the Ione, Upper Eocene of California, upon the basis of fossil plants, and with the Upper Clarno of the John Day Valley by Merriam. If it is the equivalent of the Upper Clarno the sedimentation was much more rapid in the Payette Basin.

Oligocene.—Certain marine beds at Astoria, well known through the early work of Dana, Conrad, and Condon, were the first of the entire coast to be assigned to the Oligocene. The basis upon which the correlation was first made by Dall has not as yet been discussed. This Astoria section now serves as the type section for the west-coast Oligocene, which is now known to be well developed in the adjoining states.

In Oregon, Oligocene faunas have been identified by Clark[5] and others from a number of localities, mainly in Clatsop, Columbia,

[1] W. Lindgren, *U.S. Geol. Surv.*, Folio 103, p. 2.

[2] I. C. Russell, *ibid.*, *Bull. 252*, p. 31.

[3] C. Washburne, *ibid.*, *Bull. 431*, p. 27.

[4] J. C. Merriam, *op. cit.*, X, 111.

[5] B. L. Clark, *Univ. Cal. Publ.*, *Bull. Dept. Geol.*, II, 102.

and Tillamook counties, and at Eugene, Lane County. These and other less well-known localities indicate that the Oligocene is quite extensively developed throughout northwestern Oregon, eastward to the foothills of the Cascades, and at least as far south as Eugene. Much remains to be done in connecting, or correlating, these rather isolated areas.

These Oligocene strata, aggregating several hundred feet, consist of marine shales, sandstones, conglomerates, tuffs, and basaltic intrusives, varying considerably in character from locality to locality.

The Oligocene marine fauna of Oregon is but imperfectly known, the *Molopophorous lincolnensis* and the *Acila gettysburgensis* zones of Washington being certainly recognized.

The upper Oligocene is well developed within the John Day Valley, where some 1,500 feet of sedimentaries are known as the John Day series. It is well exposed along the valleys of the John Day from Picture Gorge to Clarno, and along the North Fork to a point some distance above Monument. Other isolated localities are known outside the John Day drainage basin. The series is divisible into three lithologic and paleontologic divisions, the lower of which is characteristically composed of red, green, or white shales; the middle division by drab and bluish tuffs; and the upper by buff tuffs, rhyolite, sands, and gravels. These terrestrial beds are but little deformed, dips of 5 to 10 degrees being rather exceptional.

The remarkable vertebrate fauna is confined to the two upper divisions, the middle yielding a *Diceratherium* zone fauna of over fifty species. The upper fauna is that of the *Promerycochoerus* zone. This John Day fauna of over one hundred species is correlated with the upper portion of the White River group.

Neocene.—The Neocene of western Oregon is represented by a series of sedimentaries yielding a lower or Monterey fauna, and an upper or Empire-Merced fauna. The beds yielding the Monterey fauna have not as yet been clearly differentiated from the Astoria group, so that their distribution and geologic characteristics can be given only in the most general terms. They include, in part, the "Solon Beds" of Condon. The strata at these localities con-

sist of marine sandstones and shales of as yet an undetermined thickness.

An invertebrate Monterey fauna is reported by Arnold and Hannibal[1] from Astoria, Mountain Dale, Westpoint, Tillimook, and along the ocean shore in the vicinity of Newport. Much, if not all, of the reported Miocene in the Coast Ranges and the Willamette Valley is now assigned to the Oligocene. A fauna of over thirty species has been obtained by Hannibal at Astoria, including *Arca devincta* Conrad, *Pecten propatulus* Conrad, *Turritella oregonensis* Conrad. These are thought by him to be characteristic of the Monterey of California, which is of lower Miocene age. Marine vertebrates, including *Desmostylus hesperus* Marsh, and *Desmatophoca oregonensis* Condon, have been found in these beds in the vicinity of Newport. These important fossils point to a middle Tertiary age of these beds.

The upper Neocene beds were described by Diller[2] as the Empire and assigned to the Miocene. They are known from the Coos Bay and Port Orford quadrangles, where they consist of light-colored shales and sandstones, which are in places massive. These rocks, aggregating about five hundred feet in thickness, lie unconformably upon the folded edges of the Eocene sediments, and in turn are disconformable with the overlying Pleistocene deposits.

Dall's[3] list of 90 species of marine vertebrates from the Empire has been considerably extended by subsequent workers. This formation until recently considered of Miocene age is now thought to belong to the early Pliocene.[4]

Unconformably overlying the Empire beds at Fossil Point, Coos Bay, is a mass of heavy conglomerates known as the Coos conglomerates, some thirty feet in thickness, which has yielded a small marine fauna, considered Pleistocene by Dall,[5] but Pliocene by several other workers.

Terrestrial beds discovered by LeConte and more recently described by Williams[6] as the Eagle Creek formation occur at or near

[1] R. Arnold and H. Hannibal, *Proc. Am. Phil. Soc.*, LII, 576.

[2] J. Diller, *U.S. Geol. Surv.*, *17th Ann. Rept.*, Part I, p. 475.

[3] W. H. Dall, *U.S. Geol. Surv.*, *Prof. Paper 59*, p. 18.

[4] B. L. Clark, and R. Arnold, *Bull. Geol. Soc. Am.*, XXIX, 298.

[5] W. H. Dall, *op. cit.*, p. 19.

[6] I. A. Williams, *Mineral Resources of Oregon, Oregon State Min. Bur.*, II, 80.

the base of the Columbia lavas at Eagle Creek, Multnomah County. This formation consists of hardened ashy clay and has yielded a flora of over forty species, which is thought to be of upper Miocene age. Such a determination would place the Columbia lava in the late Miocene, or Pliocene, which is contrary to the evidence afforded by the Mascall fauna, which occurs within the John Day Valley and has yielded an extensive middle Miocene fauna.

Unfortunately this name is preoccupied by the Triassic Eagle Creek beds of the Wallowa Mountains. The Miocene formation might well be called the Warrendale formation, from the town of that name, near Eagle Creek, a tributary of the Columbia.

W. D. Smith[1] has described a series of at least four hundred feet of buff-colored tuffs occurring on the Santiam River near Cascadia, which may be correlated with the Warrendale formation, or possibly with the John Day. As yet no fossil remains have been found in these tuffs.

Lying above the Warrendale formation, which may later prove but a local interbedded deposit, is the Columbia lava, a name applied by Russell to basaltic flows occurring extensively in eastern Washington and redefined by Merriam[2] to include only the lavas younger than the John Day Oligocene and older than the Mascall middle Miocene. As thus defined the Columbia lava is a widespread formation covering large areas in eastern Oregon, eastern Washington, western Idaho, and northern California, entering into the structure of the Oregon Cascades as shown by Diller, Williams, and Smith, and occurring presumably in discontinuous areas of western Oregon.

The Columbia lava series consists of basaltic flows, often interbedded with lateritic deposits and tuffs. These vary considerably from place to place as regards number and thickness. Twenty-three have been counted on the John Day and twenty in the Columbia gorge.

East of the Cascades these flows are often but comparatively little deformed, though in places they have been faulted, resulting in the typical block-fault type of mountains. In some places this

[1] W. D. Smith, *Univ. of Oregon Bull. 16*, p. 38.

[2] J. C. Merriam, *op. cit.*, II, 304.

apparent folding may be due to pre-existing irregular topography. Along the Columbia River gorge the flows are seen to be thrown into an anticlinorium.

The age of this series of flows is definitely limited by the middle Miocene Mascall and the John Day Oligocene.

Beds unconformably overlying the Columbia lava within the John Day Valley have been named the Mascall formation.[1] These beds, aggregating about one thousand feet, consist of conglomerate, sand, ash, and tuff, and have yielded a rich vertebrate fauna and a well-defined flora,[2] of middle Miocene age.

The Pliocene of eastern Oregon is represented by the Rattlesnake,[3] Ironsides, and Idaho beds. The oldest of these, the Rattlesnake, is typically developed on Rattlesnake Creek, near the Mascall Ranch on John Day River. These beds have been recognized by Osmont in the Crooked River Valley. The Rattlesnake consists of coarse basal gravels, brown tuff, and a rhyolite flow. This formation has been deformed and in places faulted. Its vertebrate fauna, though meager, is sufficient to indicate an early Pliocene age.

Sedimentary beds at Ironside,[4] Malheur County, have recently been designated the Ironside formation. Buff-colored, sandy shales and shales of possibly two hundred feet in thickness, now deformed, yielded a small vertebrate fauna which Merriam considers as being younger than the Rattlesnake Pliocene.

Lindgren[5] has described certain lacustrine deposits along Snake River as the Idaho formation. This has not been distinctly separated structurally and lithologically from the earlier beds of the same region known as the Payette, though the presence of equine and proboscidian remains prove the presence of later beds.

PSYCHOZOIC

Pleistocene.—The Pleistocene of Oregon includes lake, glacial, and river deposits, marine conglomerates, sands, peat, and extensive igneous formations. It is yet too early to put all these widely

[1] J. C. Merriam, *op. cit.*, II, 305.

[2] F. H. Knowlton, *U.S. Geol. Surv., Bull. 204*, 1902.

[3] *Op. cit.*, p. 310.

[4] J. C. Merriam, *op. cit.*, X, 129.

[5] W. Lindgren, *U.S. Geol. Surv.*, Folio 103, p. 2.

separated and heterogeneous materials in their proper chronological order.

At many points along the Oregon coast, but especially well developed at Cape Blanco, we find marine conglomerates, sands, and shell beds lying unconformably above the Empire (Pliocene) and nearly horizontal, but with a slight southerly dip. The section at Cape Blanco is described and figured by Diller.[1]

There are two distinct horizons above the Empire here, the lower one being presumably the Cape Blanco beds of Diller which Dall has suggested may correspond to the Merced of California and hence Pliocene. The upper part with recent-looking shells is Pleistocene, without much doubt. These have been called the Elk River beds, which Arnold and Hannibal[2] correlate with the Saanich formation of Puget Sound. These investigators do not appear to make any separation of the beds overlying the Empire.

Diller notes a lithologic difference between the Blanco and the Elk River beds, chiefly in the matter of consistency. This may be of little significance. Similar Pleistocene marine deposits can be seen in similar position all along the Oregon coast to the Columbia River.

From a consideration of the above-mentioned deposits we are led to discuss the Satsop formation of Bretz,[3] in which this investigator includes some at least of these coastal gravels. His type locality for this formation is in the Chehalis Valley, Washington, and the formation is especially well represented in Oregon along the Sandy, a tributary of the Columbia River, near Portland. Bretz's description of this formation along the Sandy is as follows:

> The formation is at least 600 feet thick along the Sandy River, with the base below river-level. The material is stream-bedded gravel and sand, indurated in some places to a conglomerate and sandstone. Quartzite is a common constituent for 10 miles south of the Columbia, but has not been found more than 15 miles from the master-stream. Quartzite and basalt are the most important constituents.
>
> The Satsop formation of the lower Willamette Valley is maturely dissected, the dissection adjusted to a base-level 200 feet or more above present flood

[1] J. S. Diller, *U. S. Geol. Surv., Bull. 196*, p. 31.

[2] R. Arnold and H. Hannibal, *op. cit.*, LII, 508.

[3] J H. Bretz, *Jour. Geol.*, XXV, No. 5 (1917), 446–59.

plains. This level is recorded in the major valleys by a prominent terrace developed mostly in the Satsop formation but in places cut in the underlying basalt. This is the Cowlitz Terrace already described.

The uplands of this Satsop plain bear a red clay soil 10–15 feet deep. This grades down into a much-decomposed gravel. At a depth of 30 feet the pebbles are decayed only on the exterior. Below 50 feet most of the material is hard and ringing when struck with the hammer. Near the Columbia the clayey residual soil on the top of the Satsop formation contains scattered quartzite pebbles, hard, bright, polished, and apparently unaffected by the weathering which has reduced the associated basaltic pebbles to a structureless clay.

The present writers have examined this formation along the Sandy and the Columbia rivers near Crown Point, but have not traced it over anything like the territory covered by Bretz. Wherever they have seen it the formation appeared to be an ordinary river gravel plastered against the sides of the valleys and on benches above the present stream beds. We did not see it disappear under the andesitic lavas at any point, though we are not prepared to say that is may not do so. A deposit of gravel might very easily be laid down underneath an undercut cliff and in this way give one the impression of having been laid down first, with a lava flow rolling out on top of it later.

With these river gravels Bretz correlates, by taking a long jump, the gravels already referred to, occurring at Cape Blanco and Elk River. He also suggests the inclusion of the quartzitic gravels in eastern Oregon at The Dalles. Why not go farther east to the John Day country, where the Rattlesnake formation (Pliocene) is found to contain many quartzitic pebbles! As yet no fauna has been found in these Cascade gravels.

Fossil leaves were found in this formation by J. B. Winstanley, of Portland, and collections were made by R. W. Chaney, of the University of Chicago. Of these I. Williams,[1] in his Columbia Gorge paper, says:

> The fossil horizon is exposed three-fourths of a mile back from the Sandy River road, in the south side of the canyon of Buck Creek 25 feet above the water, beneath an overhanging cliff of conglomeratic phase in which pebbles of polished quartzite are common. Mr. Chaney states that in this one exposure of the Satsop, four genera and at least seven species of plant life are represented.

[1] I. Williams, *Ore. Bur. Mines and Geol.*, II, No. 3

They include the oak, willow, walnut, and the sequoia. The latter is apparently the living redwood of California. Both the oak and the willow likewise closely resemble their living relatives in that sister-state at the south.

There are in this Satsop flora above the Columbia basalt remains of several of the same genera found in the Eagle Creek strata below that great body of lava, but their specific characters are so markedly more modern as to brand this flora at once as belonging to a distinctly later age. On the other hand, this flora includes plants that at present grow upon the earth, most of them, however, flourishing only in the warmer climate of lower latitudes. Such equivalence to living forms might imply enforced migration, the retrieval of lost territory having not yet, to the present, been made. Or more likely, that the climate in which they grew, and prior to their displacement, was a more equable one than ours of today. In any case, similarity with land plants found elsewhere in undoubted Pleistocene strata, as well as with those of the present, affords us tentative grounds at least for saying with added confidence that the Satsop formation, as it enters into the structure of the Cascade Range, appears to belong to the Pleistocene.

The deposits at Fossil Lake and at other lakes of the semiarid region of south-central Oregon are definitely referred to the Pleistocene. First it should be stated that the avifauna and equifauna mentioned in the literature in connection with Silver Lake came from Fossil Lake a few miles northeast of Silver Lake. As there are two Silver Lakes in south-central Oregon, the name Fossil Lake ought to be used to the exclusion of that of Silver Lake.

This lake is now dried up, and the surface material consists of a light-colored mixture of sand, clay, and silts. Some of this may be a fine-grained tuff. Deposits of tufa, or lime carbonate, are found covering much of the surface about these lakes.

We cannot refer these deposits to their proper zone at the present time. In these same beds containing Pleistocene animals there were some human artifacts, chiefly arrowheads, which it is thought are of more recent origin.

Extensive and highly important collections, principally of birds and horses, have been made here by various institutions, Dr. Thomas Condon being the first scientist to explore them. The most notable studies made on this subject are by Schufeldt[1] and by Cope.[2] Many bones of the mammoth, of camels, and horses

[1] R. W. Schufeldt, *Jour. Acad. Nat Sci.*, Philadelphia (1892), No. 9.

[2] E. D. Cope, *Am. Natural.*, XXXIII, 970-82.

(*E. pacificus*) from this locality are in the Condon Museum at the University of Oregon. A flamingo is perhaps the most striking feature of this fauna. Schufeldt thought that these deposits were of Pliocene age, but Osburn and others have shown that they must be early Pleistocene.

Above the Columbia lava and the Satsop is the great pile of more recent lavas in the Cascade Range which have been found to be predominantly andesitic. A part of this series of several thousand feet of thickness is undoubtedly Pleistocene, but the lowest portion may be Pliocene and the upper portion may be Recent. These lavas make up the bulk of the several more or less eroded cones, such as Hood, Jefferson, Three Sisters, and McLoughlin, which rest upon the Cascade basaltic lava plateau.

No comprehensive article or book has been devoted to the subject of glaciation in Oregon, and very few papers of any kind have discussed it. On the highest mountains in the state, in the Wallowa Mountains and the Cascades, there are mere remnants of one-time large glaciers, and these are relatively unimportant. We have never seen a catalogue of the glaciers in Oregon and do not know exactly how many there are. In the Wallowa Mountains there is only one glacier of any consequence, and it is not large. On Mount Hood there are eight, on Jefferson four, and on Three Sisters eleven. How many there are on Mount Washington is not known. Mount McLoughlin is too far south, we believe, and not of sufficient height to have much ice upon it.

Though the existing glaciers are small in Oregon (the largest, Collier Glacier on the Sisters, being not over a mile in length) they were once much more extensive, for their despoits are found at much lower elevations.

Every class of glacial deposit characteristic of alpine glaciers can be found within the limits of the state. The largest moraine the writers have seen is the lateral moraine on the east side of Wallowa Lake in the extreme northeastern part of the state. This is about six miles long, one-fourth of a mile wide, and between six and seven hundred feet high. It is fivefold at its lower end.

Perhaps the most interesting and at the same time most puzzling phenomenon connected with the subject of glaciation in Oregon is

the erratics of granite, quartzite, and argillite to be found here and there in the Willamette and adjacent valleys in western Oregon. One of these erratics is a polished and striated quartzite bowlder about the size of one's head. The striations are unmistakably of glacial origin. Their presence has been explained, perhaps correctly, by Condon as having been dropped from icebergs floating in the "Willamette Sound." It is difficult to explain the presence of these on any other basis, as they could hardly have been brought down from the upper Willamette Valley, since no such rocks have yet been found near the headwaters of that system of drainage. However, all these rocks are found in eastern Oregon, whence they might have been transported by the Columbia.

There was undoubtedly a large body of water occupying at least the lower portion of the Willamette Valley, but this, as both Dr. Condon and his daughter, Mrs. McCornack, expressly stipulate, was in part fresh. Thus the use of the term "sound" is perhaps unfortunate. The flatness of the floor of the Willamette Valley has been attributed to the presence of this sound, but is more easily explained by aggradation and the lateral planation by the river.

A fauna from scattered localities within the Willamette Valley has been reported by Mrs. McCornack.[1] The interpretation of this fauna, which includes a horse, a bison, a mammoth, and a camel, may have an important bearing upon the "Willamette Sound" and the "Satsop" problems.

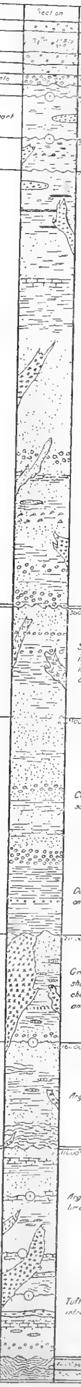
Recent.—Among the forms of deposits and events of the Recent period in Oregon we may note the following:

1. Gravels—stream, ocean littoral.
2. Talus—on the valley sides.
3. Dunes along the coast and in lake region of eastern Oregon.
4. Peat bogs in the coastal dune area.
5. Volcanic deposits in the Cascades.
6. Shore deposits, beaches, bars.

This list does not pretend to give the chronological sequence, about which there is more or less conjecture. Some of these undoubtedly are synchronous. About the first two little need be said, as these are found everywhere.

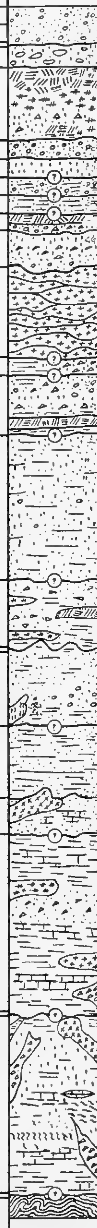
[1] Ellen Condon McCornack, *Univ. Ore. Bull.*, XII, No. 2 (1914), 13.

Era	System	Group or Series	Formation	Section	Lithology	Correlatives
Cenozoic	Recent		Alluvium		61195 Sands and gravels	
			Volcanics		61145 Rhyolitic flows, pyroclastics	
	Pleistocene		Terrace		60145 Sands and gravels	Saanich
			Elk River		60120 Shales, sands and gravels	San Pedro (?)
	Pliocene	Merced	Coos Conglomerate		60030 Conglomerate	Merced
			Empire		60000' Sandstone and shales	
	Miocene Lower	Monterey	"Solen Beds" in part		59500' Shales, sandstones, basaltic flows (?)	Monterey
	Oligocene	Astoria			57500' Shales, tuffaceous shales, and basaltic intrusions	San Lorenzo (Clark)
	Eocene Upper	Arago-Umpqua group	Tyee sandstone, Umpqua and Wilbur formations		56000' Sandstones and light colored coal seams Sandstones, shales, basaltic intrusions Impure limestone, massive micaceous sandstones and shales, andesitic intrusions. Conglomerates, sandstones, shales,	Ione Tejon
Mesozoic						



Era	System	Group or Series	Formation	Lithology	[illegible]
Cenozoic	Recent		Alluvium	[illegible] and gravels	
			Volcanics	Rhyolitic flows, pyroclastics	
	Pleistocene		Terrace	[illegible]	
			Elk River	[illegible] sands and gravels	[illegible]
	Pliocene	Merced	Coos Conglomerate	Conglomerate	San Pedro (?)
			Empire	Sandstone and shales	Merced
	Miocene Lower	Monterey	"Scien Beds" in part	Shales, sandstones, basaltic flows (?)	Monterey
	Oligocene	Astoria		Shales, tuffaceous shales, and basaltic intrusion[illegible]	[illegible]
	Eocene Upper	Arago-Umpqua group	Coaledo, Pulaski, Tyee sandstone, Umpqua and Wilbur formations	Sandstones and light colored coal seams Sandstones, shales, basaltic intrusions Impure limestone, [illegible] sandstones and shales, andesitic intrusions Conglomerates, sandstones, shales, limestone lenses, tuffs, and intrusions of diabase.	[illegible] Tejon
Mesozoic	Cretaceous Upper	Chico	Chico	Sandstones and shales with interbedded conglomerates, intrusions of serpentine and gabbro cutting the Cretaceous rocks	Chico
	Cretaceous Lower	Myrtle	Horsetown	Conglomerates, sandstones, and sandy shales	Horsetown
			Knoxville	Dark shales, thin bedded sandstones and conglomerates	Knoxville
	Jurassic	Dothan		Granodiorite bathyliths, argillite, shale, sandstone, radiolarian cherts, intrusives, andesites, and serpentines.	Franciscan (?)
		Galice		Argillites, shale, sandstone	Mariposa
	Carboniferous		Waldo-Kerby beds Gold Hill-Oregon Cave beds	Argillites, sandstones, cherts, limestones	
	Devonian		Applegate-Kane Creek beds Little Applegate-River beds	Tuffs, andesitic flows and intrusives	
	Algonkian (?)		S[illegible]	[illegible] schists	C[illegible] schists (?)
			Abrams	[illegible] schists	

GEOLOGIC COLUMN OF WESTERN OREGON



Era	System		Group or Series	Formation	Section (1)	Lithology	Correlatives
	Recent			Alluvium		30700' Sands and gravels	
				Terrace deposits		30650' Sands and gravels	
Cenozoic	Pleistocene			Glacial deposits		30600'	
				Cascade		30000' Andesitic and rhyolitic flows, dacite and tuffs.	
				Satsop		28000 Sands and gravels.	Satsop
				Fossil Lake beds (2)		27400'	
	Pliocene	Upper		Idaho beds		27330 Sands, gravels, clays	Idaho formation
				Ironside beds		27150' Buff sandy shales	
		Lower		Rattlesnake		26950' Tuffs, gravels and rhyolitic flows	Procamelus zone
	Miocene	Middle		Mascall		22650 Tuffs, ashes, and possibly gravels.	Merychippus zone
		Lower		Columbia Lava		25650' Olivine, basalts, tuffs, and intercalated gravels.	Yakima basalt
				Warrendale (3)		Carbonaceous clays and tuffs.	
	Oligocene	Upper	John Day	John Day		22655' Tuffs, sands and gravels, rhyolite. Drab and bluish tuff. Red, green, & white shales, rhyolite.	Promerycochœrus zone Diceratherium zone
	Eocene	Upper		Payette		21000' Sands, clays, and fine gravels.	Payette of Idaho
		Lower		Clarno		17000' Shales, tuffs, rhyolitic and andesitic flows.	Manastash formation
Mesozoic	Cretaceous	Upper	Chico	Chico		15000' Sandstones, conglomerates and shales. Serpentine intrusions.	Chico
		Lower	Shasta	Knoxville (?)		13000' Dark bluish, fine grained shales and sandstones	Knoxville (?)
	Jurassic	Lower		Silvies River beds		11000' Bathylithic intrusions, granodiorite. Red impure limestone	Hargrave
	Triassic	Upper	Eagle Creek series	Eagle Creek beds		10050 Calcareous shales, limestones, agglomerates, basalts, andesites, and tuffs.	Hosselkus limestone
Paleozoic	Carboniferous			Big Creek, Winterville, and Crooked River, Crook County.		5500' Dark colored argillites, cherts, clay slates, limestone lenses, greenstone, diorite, and gabbro intrusives.	? Delhi formation of Calaveras
Archeozoic	Archean (?)			Bald Mt Gneiss		500 Gneiss	

FIG. 2.—Geologic column of eastern Oregon

(1) These thicknesses are in most cases only approximations.

(2) The relationship to the Satsop is unknown.

(3) The relationship to the John Day is unknown.

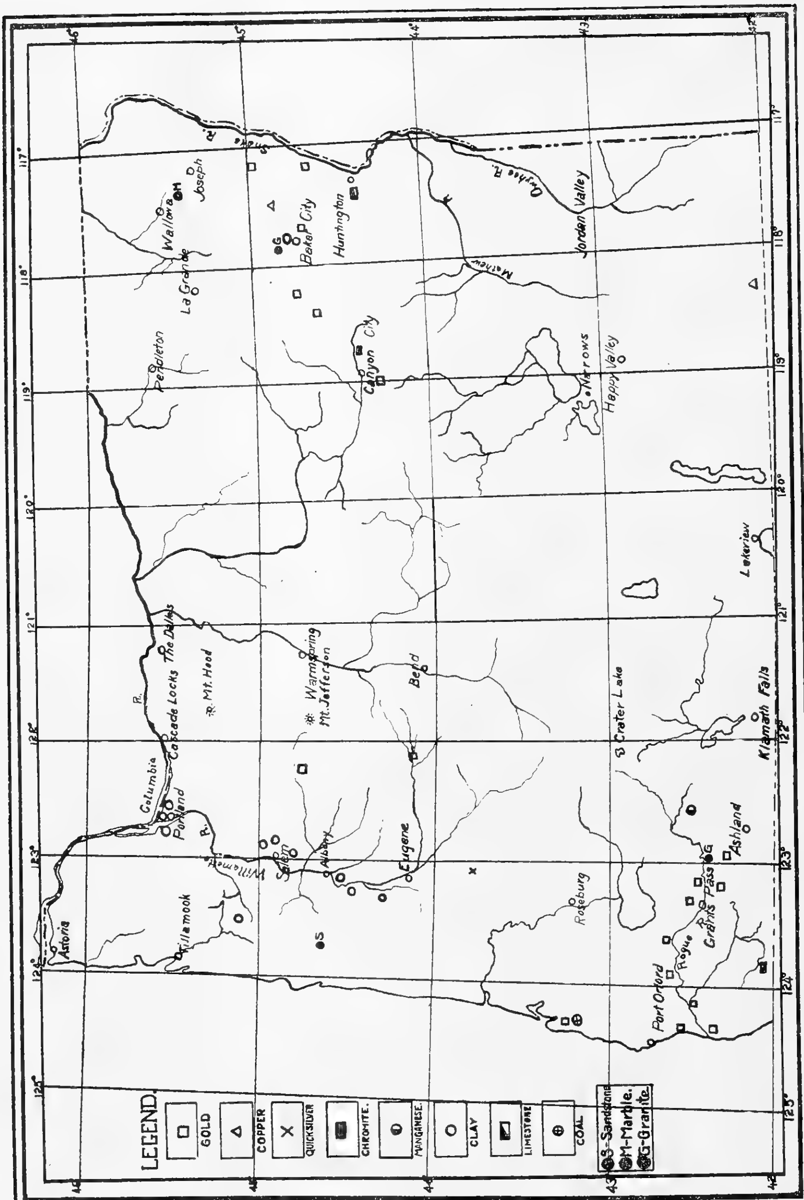


FIG. 3.—Principal mineral localities in Oregon

In the topography of the Oregon coast dunes are especially noteworthy, since Neocene and Pleistocene sandy formations outcrop throughout practically its whole length. These shifting sands have, besides resulting in dunes, caused the formation of a chain of very interesting and picturesque lakes. These lakes owe their existence to the damming up of sluggish streams by the shifting ocean sands.

Peat bogs are now forming in these dune areas, where large quantities of sphagnum moss and rhododendron leaves accumulate. In the cliffs overlooking the sea, near the top of the section in many places can be seen a bed of two feet or more of fairly solid peat. This may be of Pleistocene or Recent age, or in part both.

In various parts of the Cascades there are cinder cones and lava streams which have every appearance of being of very recent origin. Some of these may be not much over a hundred years old. Indeed very carefully sifted newspaper stories and accounts by pioneers make it reasonably clear that volcanic activity persisted in the Cascade region until a very late day. The *Portland Oregonian* reports an eruption from Mount Hood as late as 1865.

GEOLOGIC HISTORY

The basement, upon which the Oregon strata appear to lie may be represented by the Bald Mountain gneiss of the Blue Mountains. The chemical composition of this supposed Archean rock indicates a sedimentary origin. Similar gneisses in Idaho and California possibly suggest a wide extension of a sedimentary terrain subsequently removed by erosion, or covered by younger deposits.

In the late Proterozoic southwestern Oregon became a basin of deposition in which the presumably conformable Abrams and Salmon formations were developed. This epoch of sedimentation was followed by a period of folding and accompanied by metamorphism which altered these rocks to mica and hornblende schists. An erosional interval extending over several geologic periods preceded the depression, in the middle Paleozoic of this same region, allowing the sea to enter from the southwest. The earlier sediments of this marine basin, now tentatively assigned to the Devonian system record a transgressing sea, with frequent oscillations from deep to shallow waters. Little is known regarding the climatic

conditions in Oregon, yet judging from other evidences these seas elsewhere teemed with corals, indicating tropical conditions. By Carboniferous time this, or a later sea in which crinoids lived, also covered a portion of the Blue Mountains of northeastern Oregon, which approximately marks the easternmost extension of that arm of the sea. The presence of tuffs and vesicular lava in the southwest gives a glimpse of volcanic activity upon the adjacent land mass.

Continental movements culminating in the Appalachian revolution caused a general retreat of the oceans to the outer edges of the continental shelf. In Oregon the Paleozoic sediments of both the southwest and northeast were uplifted, folded, and somewhat metamorphosed, though the principal orogenic movements of the Klamath region may have occurred later.

A long erosion interval followed, longer perhaps in the southwest than in the Wallowa Mountain region, for there the record of a shallow, oscillating sea, with a shore line not far to the southeast, is found in the Eagle Creek series of Triassic age. The meager fauna suggests little of the probable mild climate that prevailed.

During the Triassic and the earlier Jurassic the Klamath region of California and Oregon was probably land, and is thought by Diller to have been the scene of vigorous volcanic activity, the record of which is still seen in California along the southern margin of that land mass. If an early Mesozoic sea ever covered that region its record is yet to be discovered.

A few lower marine Jurassic fossils from the southwestern flank of the Blue Mountains is the only record of the Jurassic of eastern Oregon. This sea, skirting the slowly rising Blue Mountains probably did not extend far into Idaho, and it may have received the sediments from a great westward-flowing stream occupying the Snake River valley of Idaho.

Late in the Jurassic an epoch of sedimentation, known as the Galice, was again initiated in southwestern Oregon by the development of a basin in which diverse marine and possibly terrestrial beds accumulated. The meager fauna from these or even later Jurassic beds in Oregon tells little of the probable boreal aspect of

these seas. In California this boreal sea followed the warmer one of the Middle Jurassic, in which reef-building corals abounded.

It is not unlikely that minor diastrophic movements intervened between the close of the Galice and the opening of the Dothan-Franciscan time. During this succeeding epoch sediments accumulated in a basin in part coextensive with that of the Galice. Some of these were terrestrial deposits developed under arid conditions, while others point to the not infrequent recurrence of marine conditions. That the climate was more humid and warmer during at least a part of this epoch seems to be vouched for by the remarkable flora obtained from Nichols, Douglas County, Oregon, which includes cycads, ferns, ginkgoes, and conifers. This remarkable flora is said to be the richest of that obtained from any Mesozoic locality.

This period of sedimentation was followed by a great mountain-building epoch at or near the close of the Jurassic, resulting in the uplift of the Sierra, Klamath, and Blue mountains to greater altitudes than they had yet attained. These movements resulted in folding and faulting of the strata involved, and were accompanied, if not caused, by the intrusion of the Siskiyou tonolite batholith, and other types of igneous rock in the southwest, giving the main structural features to the Klamath Mountains as well as greatly metamorphosing many of the rocks involved.

In eastern Oregon "after the deposition of the Trias followed another and more extensive uplift, probably the same which affected the whole of the Pacific slope. Both the Triassic and Paleozoic series were folded . . . . the Trias were violently compressed in the area now occupied by the Wallowa Mountains. The uplift was accompanied by very extensive intrusions of granular rocks."[1] Thus the Blue Mountains in late Jurassic and Cretaceous times must have been a range of imposing height having a general eastward and westward trend.

The principal metallic deposits of southwestern and northeastern Oregon are genetically related to these igneous intrusives. The earlier epoch of mineralization occurring in the Paleozoic was of

[1] W. Lindgren, *U. S. Geol. Surv., 22d Ann. Rept.*, p. 596.

lesser importance. The latest occurred after the extrusion of the Columbia lava in the Miocene, followed by late Tertiary and Quaternary concentrations as placers or secondary enrichments.

Marine conditions were again initiated in later Knoxville time by the advance of an arm of the sea along the northern flank of the then partially dissected Klamath Mountains. The erosion preceding and continuing into this epoch had partially lowered those mountains and had exposed rich quartz lodes to the actions of the streams. Gold was thus washed out and deposited in the basal gravels of the transgressing Cretaceous sea. By upper Knoxville time the cold sea-waters of that time were cutting in the Franciscan rocks near Roseburg and were possibly skirting the foothills of the Blue Mountains. The meager boreal fauna of this sea gave way to the abundant tropical life of the Horsetown Sea, which was coextensive, in southwestern Oregon at least, with that of the preceding epoch. A rich Shasta flora upon the adjacent land gives another glimpse of the forests of Oregon.

In Chico time the sea, still teeming with tropical species of Indo-Pacific affinities, entered the Rogue River basin and ultimately reached the foothills of the Blue Mountains, possibly connecting through the ancient Lassen Strait with a California sea forming the Siskiyou Island of Condon.

This marine epoch was brought to a close by the epeirogenic and orogenic movements of the Laramide revolution, resulting in the final withdrawal of the sea from eastern Oregon, the uplift of the Klamath region, the folding and faulting of the strata, and the intrusion by basic igneous rocks. It is not improbable that a minor uplift along the axis of the present Cascades occurred at that time, forming an effective barrier to the earlier Tertiary seas. A long interval of erosion followed, which is in part represented in California by the Martinez Eocene. During this time much of the Cretaceous sediment was carried away, and southwestern Oregon was reduced to a region of low relief before the next depression in western Oregon admitted a tropical Tejon Eocene sea over western Oregon as far south as Roseburg and the mouth of the Rogue River. Thousands of feet of silts and sands were deposited in this shallow sea, which at times retreated locally, permitting the

swampy conditions now indicated by seams of coal. Volcanic activity again broke forth, producing basaltic and diabasic masses, some of which still form conspicuous heights of the northern Coast Range.

The Klamath region was being still lowered by erosion, and fluvatile and lake deposits equivalent in part to the Ione Eocene were formed in local basins. Along the western flanks of the Blue Mountains considerable thicknesses of rhyolitic ash and andesitic flows of the Clarno Eocene suggest the presence of volcanic vents to the westward. Still farther east along the Idaho-Oregon boundary local changes in drainage, due perhaps to blocking of channels by lava flows, or faulting, caused the deposition of the stream and lacustrine deposits of the Payette. These terrestrial beds give evidence of a tropical flora the remains of which, accumulating in various terrestrial and estuarine basins of the state, have since changed to the valuable coal seams of the Pacific Coast.

Only slight deformative movements intervened between the Clarno Eocene and the John Day Oligocene of eastern Oregon, but in the southwest an uplift occurred at the close of the Eocene that inaugurated the conditions which during the two succeeding geologic periods produced the Klamath peneplain. In the meantime the Eocene marine sediments had been gently folded, and the northwestern portion of Oregon was again depressed, allowing the Oligocene sea to reach the region of the present site of the Cascades and extend southward at least to Eugene. Near the shore of this subtropical sea tuffaceous deposits indicate volcanic activity to the eastward. Similar activity is conspicuously represented in some of the tuffs of the John Day Oligocene, which may be in part the correlative of marine Oligocene. The terrestrial deposits of the John Day, according to Merriam, were formed along the flood plains of an old-age stream. These lowlands were the habitat of oreodons, primitive dogs, saber-tooth cats, rhinoceroses, three-toed horses, and numerous other forms well known through the classical studies made upon this fauna.

The marine Oligocene was deformed, to an extent as yet undetermined, before the advance of the less extensive Monterey Sea. These waters were still warm, possessing a fauna similar to that of

California, yet apparently deficient in diatamaceous and radiolarian remains which are associated with the petroliferous deposits of that state. Volcanic activity then became the dominant feature of the period. Olivine basalts, issuing from fissures and vents along the axis of the present Cascades and throughout eastern Oregon, formed vast floods of lava, which rose high upon the flanks of the Blue Mountains. These flows were intermittent, as is attested by interbedded lateritic deposits, frequently containing petrified wood. This epoch of volcanic activity came to a close in middle Miocene time. In the John Day region these lavas were flexed, faulted, and partially eroded before the deposition of the middle Miocene Mascall in structural or erosional basins. Along the axis of the present Cascades these flows were thrown into an anteclinorum now exposed within the gorge of the Columbia. This epoch of deformation was of more than state-wide significance, being recognized in Washington and California.

The upper Miocene record of Oregon west of the Cascades is read mainly in the details of the later history of the then peneplained Klamath region. The marine epoch of Empire time is now thought to be early Pliocene. The upper Miocene floras of adjoining states and that of the eastern Oregon Mascall indicate a moist, warm, temperate climate, in which the camel, the horse, the ancient bear, and the proboscidians thrived. By the close of the Miocene, movements again interrupted the sedimentation in the John Day region, which deformed the Mascall beds. Upon their eroded edges were deposited gravels, tuffs, and flows of the early Pliocene.

Other local lake and flood plain deposits of later Pliocene age occur nearer the Idaho line, giving evidence of the formation of structural basins or changes in drainage as yet but imperfectly deciphered. A depression of a narrow strip paralleling the present shore line developed along the coast in early Pliocene and received the marine sediments of the Empire. The fauna of this sea indicates a cooler climate. This marine epoch was brought to a close by the epeirogenic movements which elevated the entire coast, producing the gentle folds now found in the Empire, probably the faulting and warping of the Klamath peneplain, and perhaps the

formation of the block mountains of eastern Oregon. Erosion soon cut these soft Empire sediments nearly to a base level, producing a second peneplain passing eastward over the Coast Range. Differential uplift within the Klamath and Coast Range regions again rejuvenated the streams, which intrenched themselves, maintaining in some instances their old, meandering courses. In late Pliocene or early Pleistocene these same streams cut deep valleys in the then exposed continental shelf, as is now revealed by soundings. The ancient Willamette River may then have carved in part its wide valley, since deeply filled by alluvium. In the meantime the Cascades had been reduced to a region of low relief covered, near the Columbia at least, by gravels of supposed Satsop age.

Following the deposition of these gravels came the final uplift of the Coast Range of Oregon and the extrusion of andesites and rhyolites forming the superstructure of the Cascade Range and the later development of the volcanic cones now dominating the crest line. Climatic changes that had been presaged by the cooler Pliocene climate culminated in the formation of glaciers on the higher peaks of the Cascades, Stein, Blue, and Wallowa mountains. These glaciers soon extended far down their valleys. The cooler and moister climate permitted the development of extensive lakes within the now semiarid region of eastern Oregon.

The life of the earliest Pleistocene is best interpreted from the rich avifauna of Fossil Lake and the marine fauna from a few very local embayments bordering the coast.

The disappearance of most of the Pleistocene glaciers, the deepening of river canyons, the development of alluvial deposits, including auriferous gravels, and the continued volcanic activity include the salient features of late Pleistocene and Recent time.

IGNEOUS ROCKS

Igneous rocks are found conspicuously developed in three regions in Oregon: (*a*) the Blue Mountains, (*b*) the Cascades, and (*c*) the Klamath Mountains. In the Blue Mountains the dominant type is granodiorite, in the Cascades basalt and andesite, and in the Klamath serpentinized peridotite, gabbro, and granodiorite.

Table I, compiled by Mr. Fred Melzer, a Senior in the department of Geology at Oregon in 1917, gives at a glance most of the general information about our igneous rocks, such as types, localities, frequency of mention in the literature, and the literature citation. From a study of the literature we find that, judging from the number of times mentioned in the literature, the various types of basalt come first, andesites next, followed by metagabbro third, and then comes rhyolite with diabase and diorite a little farther in the rear.

The dominant rock in the Cascade region is the Columbia lava, which is basaltic. The principal rock in the Cascade superstructure is andesite. In the metalliferous districts of the southwest and northeast granodiorite is the chief rock. For a petrographic description of this and the following rocks the reader is referred to Table I.

The serpentinized peridotites in the vicinity of Port Orford are both interesting and valuable economically because of the association of chromite and nickel. According to Diller they were probably intruded in Cretaceous times.

It will be seen from the testimony of the literature that the dominant igneous activity in the state has occurred later in geologic time, in the Mesozoic and Cenozoic. Very little is definitely known of the igneous rocks of the Paleozoic, and little or nothing of the pre-Cambrian, if indeed there were any at all at that time in this state.

Chemically the rocks are alkali-calcic. According to Iddings,[1] "the 76 igneous rocks of the Cascade Mountains that have been analyzed belong in 24 magmatic divisions of the Quantitative system, 56 falling in 5 divisions: tonolose 22, lassenose 11, andose 9, hessose 8, and yellowstones 6, all of which are dosodic. Only 9 of the 76 analyzed are sodipotassic."

Steinmann[2] asserts that the average igneous rock of the South American Cordillera is similar to that of the Pacific Coast of North America. He says that the lavas of the former region are andesites, dacites, and rhyolites, and that granodiorites are the pre-

[1] J. P. Iddings, *Igneous Rocks*, II, 446.

[2] G. Steinmann, *Geolo. Rundschau*, I (1910), 13.

TABLE I

Igneous Rocks of Oregon

Rhyodacite	...	Phenocrysts: plagioclase and orthoclase in a fine quartz matrix	...	A. N. Winchell	Galice district, Josephine Co.	
Dacite	...	Phenocrysts: plagioclase and quartz; groundmass of plagioclase, quartz, etc.	Groundmass, hypocrystalline	A. N. Winchell Lindgren	Galice district, Josephine Co. Hereford, Baker Co.	
Hypersthene dacite	...	Phenocrysts: labradorite, hypersthene, brown hornblende; sometimes augite and olivine. Groundmass varies in different types	Porphyritic, groundmass varies from glassy to crystalline	Patton, pp. 3, 99–141	Crater Lake	Dacites are the latest flows seen on rim of Crater Lake.
Andesites: Hornblende andesite	Eocene or later (Calkins)	Phenocrysts: labradorite and more acid feldspar, brown pleochroic hornblende, accessory apatite and magnetite. Groundmass, andesine feldspar, etc.	Porphyritic, groundmass minutely crystalline	Calkins, pp. 128–29 Lindgren Diller	Hald's Canon Burnt River and Middle Fork, John Day Bonneville and Cascades	
Hornblende hypersthene andesite	Clarno and later (Calkins)	Phenocrysts: basic labradorite, iddingsite pseudomorphs after hypersthene, hornblende, zeolites	Porphyritic, groundmass, hyalopilitic	Calkins, p. 129 Diller	Clarno's Ferry Bonneville Mt. Hood, Cascades	Feldspars in part altered to stilbite and heulandite which Calkins calls characteristic of Clarno andesites.
Hypersthene andesite	Pleistocene Clarno (Calkins)	Phenocrysts: basic plagioclase, hypersthene, augite, magnetite, seldom olivine and hornblende	Groundmass distinguishes two types (Patton): A. Hyalopilitic B. Hypocrystalline 1. Docitic 2. Holocrystalline	Patton, pp. 69–99 Calkins, pp. 122–28 Lindgren, p. 592	Crater Lake Hald's Canon Susanville to Prairie Cascades	The andesites are the oldest of Crate-Lake effusives. Calkins' hypersthene shows alteration to iddingrite.
Augite andesite	...	Phenocrysts: plagioclase, augite, at times hypersthene, but subordinate to augite	Minutely porphyritic, groundmass somewhat ophitic	Diller	Roseburg Quadrangle Grant's Pass Quadrangle Bohemia mining district	Although no such full descriptions are given for this rock as for the foregoing, the evident subordinate character of the hypersthene makes possible distinction.
Basalts: Olivine basalt	Miocene	Basic plagioclase (labradorite); common pale brown augite, subordinate olivine, iron ore; apatite, secondary iddingsite and zeolites	Groundmass intersertal to ophitic holocrystalline	Calkins, pp. 159–65 Diller Lindgren A. N. Winchell	Eastern Oregon Coos Bay and Roseburg Quadrangles Josephine and Jackson Cos.	This includes the widespread "Columbia River Lavas."
Olivine-free basalt	Mascall (Calkins)	Basic plagioclase, augite, abundant accessory magnetite	Groundmass is typically intersertal	Calkins, pp. 165–66 Lindgren	John Day basin	This includes Winchell's auganite.
Quartz-bearing hypersthene basalt	Eocene (Calkins)	Phenocrysts: pleochroic hypersthene and green augite, olivine, quartz showing magmatic corrosion. Microlites of labradorite	Feltwork groundmass of pyroxene, feldspar, and brown glass	Calkins, pp. 134–46	Cherry Creek, John Day basin	
Hypersthenebasalt	Post-Tertiary	Very basic plagioclase, augite, hypersthene olivine, magnetite	Structure, interstitial to porphyritic	Patton, pp. 141–63	Crater Lake	Occurs only as flows from cones on outer slope of Mt. Mazama. Russel's Pleistocene basalt of southeastern Oregon may belong here.
Andesitic basalt	...	A type approaching in composition and structure Patton's hypersthene andesite above	...	Patton	Crater Lake	
Augitite	...	Pyroxene	...	A. N. Winchell	Takilma, Josephine Co.	

TABLE I

Igneous Rocks of Oregon

Name	Age	Mineral Composition	Texture	Authority	Localities	Remarks
I. PLUTONIC ROCKS						
Granites: Hornblende biotite granite	Post-Triassic	Like hornblende-biotite granite-augite altering to hornblende	....	Grant and Cady*	Haines, Baker Co.	
Soda granite	Post-Triassic	Quartz, albite, small amount of ferro-magnesian minerals, mostly chlorite	Granular	Lindgren	Sparta, Baker Co.	
Granite from White Point	....	Abundant orthoclase, some plagioclase, quartz, biotite, muscovite, and accessories	....	A. N. Winchell	White Point, Jackson Co.	
Granodiorite	Late Mesozoic	Abundant sodic plagioclase = (andesine-oligoclase), subordinate orthoclase and microcline, some quartz; biotite, green hornblende, titanite, pyrite, magnetite, apatite, and zircon	Medium-grained, hypidiomorphic, granular	Lindgren, Pardee*, Swartley* / Calkins, p. 11 S. / A. N. Winchell, Diller	Bald Mt. batholith, Baker Co. Wallowa Mts. / John Day Basin, Middle Fork / Josephine and Jackson Cos.	It is with this rock, especially in the Blue Mts., that the gold bearing quartz veins are associated.
Tonalite	....	Sodic plagioclase, quartz, hornblende or biotite, or both, and accessories	....	A. N. Winchell	Josephine and Jackson Cos.	
Diorite	....	Sodic plagioclase, hornblende or biotite, or both, accessories	Dark gray granular rock	Lindgren, A. N. Winchell, Pardee and Hewitt*	Baker Co. Josephine and Jackson Cos.	Occurs as marginal variation of granodiorite and tonalite batholiths in both localities.
Diorite porphyry	....	Larger crystals of plagioclase feldspar, augite, hypersthene, in finer matrix of same minerals plus possibly some quartz	Holocrystalline	Ira A. Williams	Shellrock and Wind Mts. Columbia River	This rock is of the plutonic type, since it occurs as an intruded batholith, in spite of the name "porphyry." It is possible that further work may identify it with one of the other types described.
Metagabbro	Pre-Tertiary	Calcic plagioclase; abundant augite, mostly altered to hornblende or chlorite; or also secondary quartz, muscovite, epidote, and kaolin	Granitic texture, at times ophitic	Lindgren, Pardee and Hewitt / A. N. Winchell, Diller	Blue Mts. / Josephine and Jackson Cos. Port Orford Quadrangle Roseburg Quadrangle	These rocks are alteration products of fresh gabbro, which itself is nowhere prominent. Winchell employs the term. Sousurite (=Metagabbro).
Norite	....	Plagioclase and inclosed hypersthene; intergrown with pyrrhotite, chalcopyrite, etc.	....	A. N. Winchell	Chisholm's copper mine on Evans Creek, Jackson Co.	
Peridotite	Paleozoic (Pardee)	Olivine; pyroxene, amphibole, or both	Coarsely crystalline, heavy, dark rock	A. N. Winchell, Pardee and Hewitt*	Riddle, Douglas Co. Along McCully's Fork, Sumpter	
Dunite	....	Olivine; little pyroxene or amphibole	Olivine, often altering to serpentine	A. N. Winchell	Spanish Gulch and Beach Cr. John Day Valley. Waldo Mine at Takilma, Josephine Co.	Winchell mentions Dunite as a variation of peridotite, in the case where olivine becomes the dominant constituent.
Pyroxenite	Pre-Eocene (Calkins)	Pyroxene	Coarsely crystalline	Calkins, p. 118, A. N. Winchell	Red Mt.	The two varieties described differ considerably.
Diabase	Eocene (Diller)	Augite, generally uralitized; lime-soda feldspar; sometimes olivine	Fine-grained, dense rock, ophitic structure	Diller, Lindgren	Roseburg Quadrangle Blue Mts.	
II. HYPERBYSSAL (DIKE) ROCKS						
Granite porphyry	Pre-Eocene	Phenocrysts: orthoclase; quartz; plagioclase; in groundmass biotite, apatite, magnetite and zircon	Porphyritic, holocrystalline groundmass	Calkins, p. 117	Spanish Gulch, Wheeler Co.	
Syenite porphyry	....	Orthoclase and hornblende	Porphyritic	Butler and Mitchell	Curry Co., Mt. Emily	The descriptions given for these two types are not sufficiently detailed to enable placing them accurately.
Granodiorite porphyry	....	Feldspar and hornblende	Fine groundmass	Swartley	Blue Mts.	
Aplite	....	Abundant microcline or orthoclase, or both, and quartz. Some plagioclase, biotite, and accessories	....	A. N. Winchell, Pardee, Swartley	Josephine and Jackson Cos. Blue Mts.	
Tonalite-aplite	....	Plagioclase and quartz, little biotite or hornblende	....	A. N. Winchell	Grant's Pass, Josephine Co.	
Pegmatite	....	Quartz and microcline, coarse muscovite, little plagioclase	Coarse texture	A. N. Winchell, Pardee, Lindgren	Evans Creek, Jackson Co. Blue Mts.	Lindgren describes a rare pegmatite from the Coyote Hills, Baker County.
Dacite prophyry	....	Phenocrysts: feldspar (labradorite), less prominently quartz, some hornblende or chlorite	Porphyritic; crystalline groundmass of quartz and feldspar	Diller	Port Orford Quadrangle Bohemia mining region Grant's Pass, Josephine Co.	
Malchite	....	Abundant sodic plagioclase, hornblende, sometimes quartz	Aplitic texture	A. N. Winchell	Ashland mine and other localities in Josephine and Jackson Cos.	Winchell's malchite is very closely related to Diller's dacite porphyry, the main difference being texture.
Kersantite	....	Biotite and plagioclase	....	A. N. Winchell, Lindgren	Josephine and Jackson Cos. Blue Mts.	
Spessartite	....	Abundant hornblende and some plagioclase	....	A. N. Winchell	Near Jacksonville	
III. VOLCANIC ROCKS						
Rhyolite	Eocene or later (Calkins)	Phenocrysts: quartz, alkali feldspar (orthoclase or sanidine), oligoclase, accessories	Light-colored rocks, glassy groundmass, often devitrified in whole or part	Calkins, pp. 141 and 152, Diller, Lindgren, Pardee, Winchell	Clarno's Ferry, Antelope Valley } John Day region / Roseburg Quadrangle / Blue River mining district / Blue Mts. / Josephine and Jackson Cos.	Calkins and Lindgren describe types with microcrystalline and cryptocrystalline groundmass. Calkins also described a fibrous groundmass. Sometimes the groundmass shows considerable alteration
Spherulitic type	Eocene	Phenocrysts: quartz, sanidine, and acid plagioclase, all sparingly present	Lithoidal groundmass containing large and small spherulites	Calkins, p. 138	Current Creek Hill, John Day region	
Obsidian	....	....	Glassy acid rock	Russel	S.E. Oregon	
Rhyodacite	....	Phenocrysts: plagioclase and orthoclase in a fine quartz matrix	....	A. N. Winchell	Galice district, Josephine Co.	
Dacite	....	Phenocrysts: plagioclase and quartz; groundmass of plagioclase, quartz, etc.	Groundmass, hypocrystalline	A. N. Winchell, Lindgren	Galice district, Josephine Co. Hereford, Baker Co.	
Hypersthene dacite	....	Phenocrysts: labradorite, hypersthene, brown hornblende; sometimes augite and olivine. Groundmass varies in different types	Porphyritic, groundmass varies from glassy to crystalline	Patton, pp. 3, 99–141	Crater Lake	Dacites are the latest flows seen on rim of Crater Lake.
Andesites: Hornblende andesite	Eocene or later (Calkins)	Phenocrysts: labradorite and more acid feldspar, brown pleochroic hornblende, accessory apatite and magnetite. Groundmass, andesine feldspar, etc.	Porphyritic, groundmass minutely crystalline	Calkins, pp. 128–29, Lindgren, Diller	Hald's Canon / Burnt River and Middle Fork, John Day / Bonneville and Cascades	
Hornblende hypersthene andesite	Clarno and later (Calkins)	Phenocrysts: basic labradorite, iddingsite pseudomorphs after hypersthene, hornblende, zeolites	Porphyritic, groundmass, hyalopilitic	Calkins, p. 129, Diller	Clarno's Ferry / Bonneville / Mt. Hood, Cascades	Feldspars in part altered to stilbite and heulandite which Calkins calls characteristic of Clarno andesites.
Hypersthene andesite	Pleistocene Clarno (Calkins)	Phenocrysts: basic plagioclase, hypersthene, augite, magnetite, seldom olivine and hornblende	Groundmass distinguishes two types (Patton): A. Hyalopilitic B. Hypocrystalline 1. Docitic 2. Holocrystalline	Patton, pp. 69–99, Calkins, pp. 122–28, Lindgren, p. 592	Crater Lake / Hald's Canon / Susanville to Prairie / Cascades	The andesites are the oldest of Crater Lake effusives. Calkins' hypersthene shows alteration to iddingrite.
Augite andesite	....	Phenocrysts: plagioclase, augite, at times hypersthene, but subordinate to augite	Minutely porphyritic, groundmass somewhat ophitic	Diller	Roseburg Quadrangle / Grant's Pass Quadrangle / Bohemia mining district	Although no such full descriptions are given for this rock as for the foregoing, the evident subordinate character of the hypersthene makes possible distinction.
Basalts: Olivine basalt	Miocene	Basic plagioclase (labradorite); common pale brown augite, subordinate olivine, iron ore; apatite, secondary iddingsite and zeolites	Groundmass intersertal to ophitic holocrystalline	Calkins, pp. 159–65, Diller, Lindgren, A. N. Winchell	Eastern Oregon / Coos Bay and Roseburg Quadrangles / Josephine and Jackson Cos.	This includes the widespread "Columbia River Lavas."
Olivine-free basalt	Mascall (Calkins)	Basic plagioclase, augite, abundant accessory magnetite	Groundmass is typically intersertal	Calkins, pp. 165–66, Lindgren	John Day basin	This includes Winchell's auganite.
Quartz-bearing hypersthene basalt	Eocene (Calkins)	Phenocrysts: pleochroic hypersthene and green augite, olivine, quartz showing magmatic corrosion. Microlites of labradorite	Feltwork groundmass of pyroxene, feldspar, and brown glass	Calkins, pp. 134–46	Cherry Creek, John Day basin	
Hypersthenebasalt	Post-Tertiary	Very basic plagioclase, augite, hypersthene olivine, magnetite	Structure, interstitial to porphyritic	Patton, pp. 141–63	Crater Lake	Occurs only as flows from cones on outer slope of Mt. Mazama. Russel's Pleistocene basalt of southeastern Oregon may belong here.
Andesitic basalt	....	A type approaching in composition and structure Patton's hypersthene andesite above	....	Patton	Crater Lake	
Augitite	....	Pyroxene	....	A. N. Winchell	Takilma, Josephine Co.	

vailing intrusives. In this connection Becker and W. D. Smith have repeatedly called attention to the relation between the igneous rocks of the Philippines and of Oregon. If we pass a great circle along the axis of the Cascades we shall find that it will pass remarkably close to the Cordilleras of Japan and the Philippines, and it is only to be expected that we would find this petrographic similarity along such a great and persistent tectonic line.

Definite figures as to the size of the intrusive batholiths in Oregon are at present unavailable. In the Blue Mountains the granodiorite is very prominent and attains elevations close to 10,000 feet and covers hundreds of square miles, while in the Cascade region it is seen in one or two localities only, and these low down and in very limited exposures. In the Siskiyou region (southwest) also there are large masses of granodiorite.

ECONOMIC GEOLOGY

In 1867 the mineral production of Oregon, according to government estimates at that time, was about twenty million dollars and was practically, if not entirely, from gold placers.

In 1917 the value of the mineral products of the state which were mined amounted to about $3,500,000. The year 1918 saw slightly less, owing to war conditions. A few years ago the production was almost nil, so that we are now on the upgrade again, and a substantial gold-mining industry largely from quartz lodes is being established.

On the mineral map (Fig. 3) are shown the principal mineral localities in the state. It will be seen from a glance that the two metalliferous districts are in the southwest and in the northeast, the Siskiyou and Blue Mountains respectively. Baker County produces the larger part of the gold of Oregon, and the Cornucopia district is the leading district of that county.

While there are many copper prospects, the most noteworthy are those near Homestead on the Snake River, and those near Waldo, twenty miles southwest of Grant's Pass, in the southwestern part of the state.

During the war there was a rather notable development of the chromite industry in these two regions, and one manganese locality

(Lake Creek) was being vigorously prospected, with the hope of a substantial production very soon.

Some platinum is recovered with gold in the beach placers to the north and south of Marshfield, but the yield has not yet had any appreciable effect on the industry.

Nickel deposits occur near Riddles, Douglas County, but no production is reported at the present time.

One quicksilver mine is located near Cottage Grove, Lane County, which, however, has not had a very prosperous history.

Common brick and drain tile are made at many localities in Oregon, but clays suitable for pottery of the better grades have either not been located, or if known, have not been worked.

All attempts to find oil in commercial quantities in Oregon have so far failed. At the present time drilling is being done near Waldport on the coast, and near Roseburg and Vale on the eastern boundary of the state. So far no success has been met in these undertakings. Near McMinnville, Yamhill County, there are several salt springs and gas wells, one of which in Polk County illuminates a ranch house and is used for cooking. This well has given off natural gas for over thirty years. No scientific development of this field has yet been undertaken. It seems to be the most promising place in Oregon for natural gas, and possibly petroleum. Some "shows" of oil have just recently been reported from a Harney County (southeastern Oregon) well, now down to 1,241 feet.

A fair grade of sub-bituminous coal of Tertiary age is mined in the small basins of marine Tertiaries near the coast. The production is small and comes from two or three small mines. The daily output probably has never exceeded fifty tons.

A great deal of crushed stone, mainly basalt and diabase, is utilized annually on our highways. Limestone is found in both the northeast and southwest portions of the state. The product is distributed largely by the State Lime Board.

The most valuable and unique decorative stone, a handsome black marble, anywhere in the state and perhaps anywhere in the Pacific Northwest is quarried near Enterprise, Wallowa County.

The state of Oregon cannot be said to be a mining state, though it has a promising future in this direction. The state is very

wisely doing something to aid this important industry in supporting a State Bureau of Mines; an appropriation of $50,000 for the biennium has just been granted it.

MINERAL PRODUCTION IN OREGON*

FOR 1917

Gold	$1,491,798.00
Platinum	65 ounces
Silver	125,656 fine ounces
Copper	2,474,487 pounds
Chromite	6,700 tons
Lead	28,000 pounds

NON-METALS, 1916

Coal	42,592 tons
Mineral water	30,920 gallons
Building sand and gravel	161,761 tons
Crushed stone (1917)	282,732 tons

*By courtesy of Charles G. Yale, statistician, United States Geological Survey.

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SOME SUBORDINATE RIDGES OF PENNSYLVANIA

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The topography of the folded mountain district of Pennsylvania consists of the narrow valleys and long, even-crested ridges cut by occasional water gaps and wind gaps which are familiar to the geologist and geographer the world over. For nearly a third of a century, since the publication of the epoch-making essay by Davis,[1] this region has been classic for the study of the peneplain. The tops of the even-crested ridges are said to represent the remnants of a surface which has been variously named the Cretaceous baselevel lowland,[2] the Schooley peneplain,[3] and the Kittatinny peneplain.[4] With the precise dates of formation of this supposed peneplain and the valley lowlands, generally called the Harrisburg peneplain,[5] we are not concerned here.

The formations sufficiently resistant to be ridge makers in Center County and neighboring counties are the Oneida and Medina sandstones of the earlier geologists, now known as the Oswego and Tuscarora respectively, separated stratigraphically by 490 to 850 feet[6] of the Juniata formation, consisting of soft red shales and sandstones. Of the two sandstones the Tuscarora is by far the more resistant to erosion, and accordingly in many instances

[1] W. M. Davis, "The Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, I, No. 3 (1889), pp. 183–253.

[2] *Ibid.*, p. 198.

[3] W. M. Davis and J. W. Wood, Jr., "The Geographic Development of Northern New Jersey," *Boston Soc. Nat. Hist., Proc.*, XXIV (1890), 377.

[4] Bailey Willis, "The Northern Appalachians," *The Physiography of the United States, Nat. Geog. Soc., Mon.*, I, No. 6 (1895), p. 189.

[5] M. R. Campbell, "Geographic Development of Northern Pennsylvania and Southern New York," *Geol. Soc. Am., Bull.*, XIV (August 5, 1903), 283–84.

[6] E. S. Moore, Unpublished data. Also Charles Butts, "Geologic Section of Blair and Huntingdon Counties, Central Pennsylvania," *Am. Jour. Sci.*, XLVI (September, 1918), 536.

on the limbs of close folds the topography finds expression in the close association of two ridges of different heights, usually with an intervening lowland on the soft Juniata formation. The discrepancy in height is not universal, as in several places in the Bellefonte quadrangle the Oswego ridges equal and even exceed in height those of the Tuscarora. It is the purpose of this article to show that these "subordinate ridges" as Willis[1] styles them, are more numerous than hitherto suspected, that their origin and existence have not been explained satisfactorily by physiographers, and that they constitute a menace to the validity of the Cretaceous peneplain theory.

The existence of subordinate ridges is noted by Willis[2] as follows:

> The simple monoclinal ridge which has been described is the typical but not the more common form of the Appalachian ranges. They become complex by association of parallel ridges. Thus on the inner slopes of Jacks and Stone mountains, about Kishicoquillas valley, there is a very marked bench or terrace, which appears as a broad step in the mountain slope. In other localities, when the outer edge of such a terrace is higher than its surface nearer the mountain, there are narrow ravines separating the terrace edge as a low ridge more or less distinct from the mountain itself. . . . . Elsewhere, again, ... the subordinate ridge may stand at a level equal with the continuous crest, and it then appears as a distinct monoclinal ridge.

The Stone Mountain referred to is the southernmost of the series of great consecutive ridges known as the Seven Mountains, which bound the Nittany valley on the south and is immediately north of the Kishicoquillas valley.

Davis[3] recognizes the existence of subordinate ridges:

> The beds of intermediate resistance, the Oriskany and Chemung sandstones, had not been worn down to baselevel at the close of the Tertiary cycle; they had indeed lost much of the height that they possessed at the close of the previous cycle, but they had not been reduced as low as the softer beds on either side. They were only reduced to ridges of moderate and unequal height over the general plain of the Siluro-Devonian low country, without great strength or relief but quite strong enough to call for obedience from the streams along side of them.

[1] Willis, *op. cit.*, p. 182. [2] *Ibid.*, p. 182.

[3] W. M. Davis, "The Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, I, No. 3 (1889), pp. 243–44.

Again, in another article, he[1] says: "The weaker Siluro-Devonian beds are generally reduced to a lowland farming country, except where the Oriskany sandstone or a Chemung conglomerate of more resistance than the adjacent beds rises in ridges of moderate height. The hard Medina and Carboniferous sandstones hold their crests close to the Cretaceous peneplain."

Professor Davis assumes that the original height of the Oriskany and Chemung ridges equaled that of the Cretaceous peneplain surface but offers no confirmatory data. Apparently he does not distinguish clearly between the heights of the Oswego and Tuscarora ridges, but he may have this discordance in mind when stating[2] that the Medina crests accord with "geographic" rather than "geometric" exactness.

Years later Stose,[3] in comparing the high, even crest of Cross Mountain with the low, "comby" top of Cove Mountain in the Mercersburg-Chambersburg region in southern Pennsylvania, says: "It is apparent that Cove Mountain once stood at approximately this altitude, but has been lowered by the active erosion of the relatively narrow exposure of upturned rocks." Cross Mountain is supposed to be part of the old peneplain surface. Farther on in the same paper he says: "These two level tracts [referring to areas on South Mountain] are undoubtedly remnants of the old peneplain, preserved at the height of 2,000 feet. The monoclinal ridges along the front of the mountain, which once stood at this same altitude, have been reduced by erosion to 1,700 and 1,900 feet."[4] In these two quotations the height of a lower ridge is explained by reduction from the original peneplain.

Reverting to the Nittany valley and the Seven Mountains district, the following are altitudes[5] (obtained by barometer) on

[1] W. M. Davis, "The Geological Dates of Origin of Certain Topographic Forms on the Atlantic Slope of the United States," *Geol. Soc. Am., Bull.*, II (July 2, 1891), 572.

[2] *Ibid.*, p. 560.

[3] G. W. Stose, "Physiographic Studies in Southern Pennsylvania," *Jour. Geol.*, XII (1904), 476.

[4] *Ibid.*, p. 478.

[5] Charles E. Billin, "Map of Adjoining Portions of Huntingdon, Mifflin, Centre, and Union Counties," *Sec. Geol. Surv. Pa., Rept. of Progress S*, 1878.

the Tuscarora summits south of Potters Mills and Boalsburg: Broad Mountain, 2,300 feet; Millikens Knob, 2,200 feet; a crest two miles south of Boalsburg, 2,300 feet; the mountain on road south of Pine Grove Mills, 2,010 feet; Roberts Knob, 2,410 feet; and Bear Meadows Mountain, 2,100 to 2,200 feet. The same map gives the following readings for the Oswego ridge summits: a ridge running from Bear Meadows north of Roberts Knob 26 miles northeast to Woodward, 1,700 feet average, attaining 1,800 feet in a few places; a corresponding ridge one mile southeast of the preceding on the other limb of the syncline, averages 1,800 feet for many miles; Tussey Knob, east of Boalsburg, rises to an altitude of 2,100 feet, rapidly sinking to the southwest to 1,600 and 1,700 feet average.

Making allowance for possible slight inaccuracies in these map elevations a distinct discordance in height between the summits of the Oswego and Tuscarora ridges, in general, becomes manifest from the foregoing data. This discordance may be observed in the field, either from one of the higher and more commanding points on the Nittany valley lowland, or from some coign of vantage in the Seven Mountains, such as Roberts Knob. After six years' residence in the Nittany valley the writer is convinced that this difference in summit levels in the central Pennsylvania district is an important factor which cannot be passed over with the facility of some previous writers.

Space does not permit here the enumeration of instances of the difference in heights of adjacent mountain ridges in other states, but one example will show how universal the phenomenon is. In the Hancock, Maryland-West Virginia-Pennsylvania quadrangle the Cretaceous peneplain has been obliterated entirely in all probability, according to Stose,[1] but is preserved in the 2,000- to 2,200-foot summit of Cacapon Mountain in the Pawpaw quadrangle. This author[2] distinguishes between the Somerville (New Jersey peneplain) terrace[3] varying from 600 to 850 feet in elevation,

[1] G. W. Stose and C. K. Swartz, "Pawpaw-Hancock Folio, Md.-W. Va.-Pa.," *U.S. Geol. Surv.*, No. 179 (1912), pp. 19–20.

[2] *Ibid.*, p. 20.

[3] Davis and Wood, *op. cit.*, pp. 391–92.

the so-called Harrisburg peneplain level of 700 to 1,000 feet shown in many even-topped ridges and intermontane floor areas, a series of ridges averaging 1,200 feet in height, which he correlates with the Weverton, Maryland, peneplain,[1] and "remnants of intermediate erosion plains" from 1,550 to 1,700 feet in height.

Facts such as the foregoing give rise to doubts and queries which are of more than local significance. To admit the inadequacy of the Tertiary erosion to reduce completely some subordinate ridges to the valley-plain level seems to be overlooking the question of their origin as much as does the affirmation that the height of subordinate ridges represents a lowering and modification of an original, higher peneplain surface. As the geologist follows for miles two closely parallel ridges of even crests but of different heights, he is likely to think, as the writer does, that the origin of the two is the same, and that any explanation of the method of development of the one should be applicable to the other also. If the one represents a portion of the dissected and mutilated surface of an older peneplain, likewise, by the same reasoning, the other must represent something; but by no stretch of the imagination can some of the lower ridges of Pennsylvania be considered peneplain remnants.

Many years ago Hayes[2] expressed the belief that a lower ridge with even crest can be produced by reduction from a higher peneplain, as "corrasion is practically absent and only the forces of erosion are in play. Hence if the ridge was originally level it might remain so indefinitely or until it had been reduced far below the former surface of the baselevel plain."

Dr. T. C. Hopkins,[3] whose experience in central Pennsylvania entitles him to express an opinion, explains the development of these low ridges—the terraces of "terraced mountains"[4]—by

[1] Arthur Keith, "Geology of the Catoctin Belt," *U.S. Geol. Surv., Fourteenth Ann. Rept.*, 1892–93, Part 2, p. 388. Also W. B. Clark and E. B. Mathews, "The Physical Features of Maryland," *Md. Geol. Surv.*, VI (1906), 87, 88.

[2] C. W. Hayes, "Physiography of the Chattanooga District, in Tennessee, Georgia, and Alabama," *U.S. Geol. Surv., Nineteenth Ann. Rept.*, 1897–98, Part 2, p. 27.

[3] Recent personal communication to the writer.

[4] T. C. Hopkins, *Elements of Physical Geography* (1908), pp. 338–39.

reduction from the original peneplain; but he believes that the stratigraphic sequence of the rock series in the Nittany valley region must be taken into account in this connection. He lays emphasis upon the fact that the Tuscarora is underlain by the Juniata, a formation comparatively soft but not nearly as soft as the Reedsville (Utica), which consists entirely of very fissile shale. Thus the Oswego ridges would tend to become undermined faster than those of the Tuscarora, and this fact, coupled with the initial difference in weathering quality between the two sandstone formations, would result in a consistent difference in height of the ridge crests.

Explanations of the present height of the lower ridges, involving a process of reduction from former higher ridges, would seem risky in view of the lengths to which such arguments can be carried. Once admitting the possibility of the lower ridges maintaining their even crests and owing their ultimate origin to differential erosion, is it illogical to explain the even crests of the higher ridges by gradual erosional development contemporaneous with and subsequent to the long period of folding? In short, arguing from the topography of the ridges only, is it necessary to postulate a Cretaceous peneplain at all?

The writer has no alternative theory to suggest and no view to advocate, but merely raises the question, feeling that the Cretaceous peneplain theory does not explain adequately the existence of these minor ridges.

Of late the word "peneplain" has been used rather loosely and has been applied to conditions where direct proof is lacking. It is easy to conclude hastily that a ridge or series of ridges represents a peneplain, but much harder to prove such a statement. By no means is every ridge or upland remnant the remains of a peneplain, and a word of caution to workers in this field seems in order.

Professor A. M. Miller[1] may voice the feelings of others than himself in the following words:

> . . . . when one examines the literature of modern physiography and sees the readiness with which an "uplifted and dissected peneplain" is invoked

[1] A. M. Miller, "Wind Gaps," *Science*, N.S., XLII, No. 1086 (October 22, 1915), p. 573.

to explain every even sky-line or approximate uniformity in heights of mountain summits, while every peculiarity in drainage is accounted for as an inheritance from a past cycle of erosion, overlooking in many cases a simpler explanation involving only "processes now in operation"; he wonders if there does not lurk therein somewhat of the old catastrophism.

The writer's thanks are due to Professors Davis and Hopkins for valuable criticism and suggestion in preparing this paper.

GLACIAL FEATURES ON THE SOUTH SIDE OF BEARTOOTH PLATEAU, WYOMING[1]

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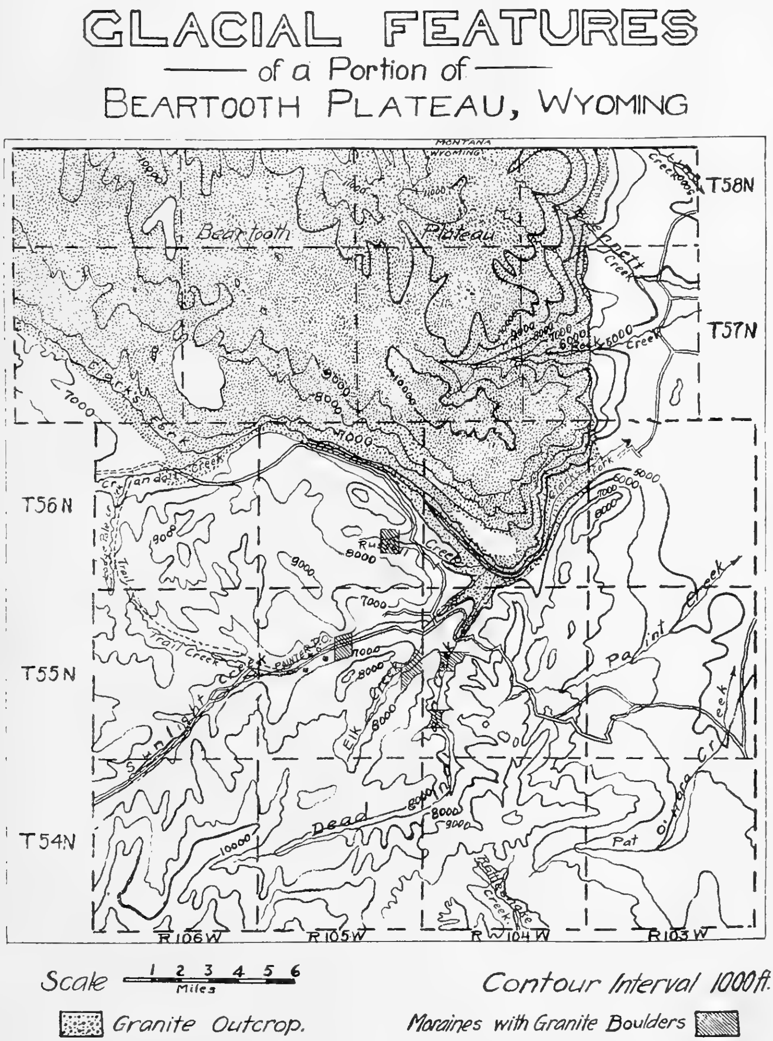
During the summer of 1916 the writer spent a number of days in the basin of Clarks Fork, along the southern margin of the Beartooth Plateau. In the course of the work there several interesting glacial features were noted. The general situation, together with the localities mentioned, are shown on the accompanying map, compiled from the Shoshone National Forest Map and from the Crandall Quadrangle.

That portion of the Beartooth Plateau lying between Clarks Fork and the Wyoming-Montana state boundary has been severely glaciated. The plateau averages over 10,000 feet in elevation and consists of bare, rounded knobs of granite, interspersed with lakes and swamps. Several of the northward-flowing streams that rise south of the state line head in typical cirques, occupied by small lakes. Glacial striae were noted at several points. The valleys of Line Creek and Bennett Creek, near where they emerge from their canyons in the granite on to the plains of the Bighorn Basin, are occupied by well-marked moraines. Little Rock Creek shows distinct evidences of glaciation but has a less pronounced moraine at the canyon mouth. There are slight evidences of a moraine at the mouth of the Clarks Fork canyon itself. On the south wall of that canyon numerous granite bowlders are to be seen several hundred feet above the contact of the Cambrian on the pre-Cambrian granite.

It is, however, in the valleys of Dead Indian Creek, Elk Creek, Sunlight Creek, and Russell Creek that the most interesting conditions obtain. In the Sunlight basin, a well-defined moraine occurs along the line between sections 15 and 16, T. 55 N., R. 105 W. It is referred to by Hewett, who says of it, "Sunlight Basin appears

[1] Published by permission of the Wyoming state geologist.

to owe its origin to the damming of a deep glacial valley by a terminal moraine, which is a prominent feature a mile below Painter



post-office, and behind which an accumulation of glacial gravel and lake sediment has formed the present valley floor."[1]

[1] D. F. Hewett, "Sulphur Deposits of Sunlight Basin, Wyoming," *Bull. U.S. Geol. Surv. No. 530*, p. 352.

Hewett failed, however, to call attention to the most marked and interesting feature of the moraine, namely, that the bowlders of which it is composed consist largely of granite, and this in spite of the fact that a careful search for many miles revealed no granite outcrops *up the valley* from the moraine. A glance at Hague's map of the Crandall Quadrangle[1] shows that in his mapping he located no granite outcrops in Sunlight valley within the area of that quadrangle, that is, in the area above the moraine. Almost as striking as the dominance of the granite in the moraine is the relative scarcity of andesite, although not far above the moraine in question the andesite walls of the basin close in, almost entirely cutting out the sedimentary series.

In view of the above-mentioned conditions the conclusion seems inevitable that the glacier moved up the valley, not down. The broad U-shape of the valley above the moraine may be due in part to glacial scour, the glacier at one time having occupied a more advanced position than it did when the moraine in question was being built. It is more than probable, however, that the U-profile is largely the result of the glacial fill resulting from deposition in the valley when occupied by the ice-dammed lake. Much of the old lake bed is still very flat and swampy.

Along Elk (Elkhorn) Creek, on the line between sections 13 and 24, T. 55 N., R. 105 W., is another well-marked moraine, in the bowlder-clay of which were noted striated bowlders of limestone, granite, and Deadwood flat-pebble conglomerate. Very little andesite occurs in the moraine, though the andesite walls close in completely, only about three miles above. A careful search up creek from the moraine to where the andesite covers all the older rocks shows no exposures older than the Madison limestone (Mississippian), although both granite and Deadwood (Cambrian) conglomerate bowlders were found occurring abundantly in the moraine. Again the conclusion is inevitable that the ice moved up the valley.

Similar conditions were noted well toward the head of Russell Creek, where moraines with very little andesite and much granite were found resting directly on andesite outcrops. Along Lodge

[1] Arnold Hague, *Absaroka Folio*, No. 52.

Pole trail, on the pass at the head of Lodge Pole Creek, granite bowlders were found high on the andesite slopes, nearly 1,500 feet above the contact of the Paleozoic series on the granite.

Similarly moraines on Dead Indian Creek carry much granite, and granite bowlders were noted on andesite outcrops on the south side of the low pass between the head of Dead Indian Creek and Rattlesnake Creek. This occurrence is eight miles south of any granite outcrop and nearly 2,000 feet above the contact of the Paleozoic upon the pre-Cambrian, near the mouth of Dead Indian valley.

In the light of these facts it would seem that the Beartooth Plateau was occupied by an ice cap that sent several tongues eastward into the edge of the Bighorn Basin, and a number southward across the Clarks Fork Canyon several miles *up the valleys* of Sunlight, Elk, Russell, and Dead Indian Creeks.

Reviews

The Permo-Carboniferous Ammonoids of the Glass Mountains, West Texas, and their Stratigraphical Significance. By Emil Böse. University of Texas Bulletin, No. 1762, Nov. 5, 1917.

The cephalopod faunas of the Permian are still imperfectly known in spite of the work of forty years in many parts of the world. The classic works of Karpinsky in Russia, Waagen in India, C. A. White in Texas, and Gemmellaro in Sicily have furnished the bulk of our knowledge of these interesting transitional forms. Dr. Böse has added a fifth to these classics, in his studies of the ammonoids of western Texas.

The bulletin contains 241 pages of text, illustrated by 11 quarto plates of halftones.

Dr. Böse describes the following formations and new species, from the base up, ranging from the base of the lower Permian to near the middle of the upper Permian.

1) Wolfcamp formation, with *Daraelites texanus*, *Uddenites schucherti*, *Uddenites minor*, *Gastrioceras modestum*, *Schistoceras diversecostatum*, *Paralegoceras incertum*, *Agathiceras frechi*, *Marathonites vidriensis*, *Marathonites sulcatus*, *Marathonites j. p. smithi*, *Vidrioceras uddeni*, *Vidrioceras irregulare*.

2) Hess formation, with *Prothalassoceras welleri*, *Marathonites hargisi*.

3) Leonard formation, with *Medlicottia whitneyi*, *Gastrioceras altudense*, *Perrinites vidriensis*, *Perrinites compressus*, *Paralecanites altudensis*.

4) Word formation, with *Medlicottia burckhardti*, *Gastrioceras roadense*, *Paraceltites multicostatus*, *Agathiceras girtyi*, *Adrianites marathonensis*, *Stacheoceras bowmani*, *Stacheoceras gilliamense*, *Waagenoceras dieneri*.

No. 1 is called the zone of Uddenites; No. 2, zone of Prothallassoceras; No. 3, zone of Perrinites; No. 4, zone of Waagenoceras.

On table I is given a correlation table of the Permo-Carboniferous cephalopod-bearing beds of the world, and the position of the Texas beds in the column.

The previously known genera, Daraelites, Paralecanites, and Adrianites are added to the American Permian fauna, and also a true

species of Waagenoceras, those formerly assigned to that genus being shown to belong to a new genus, Perrinites. The following new genera, or subgenera, are described: Uddenites of the Medlicottidae; Marathonites, Vidrioceras, and Perrinites of the Arcertidae; Prothallassoceras of the Thalassoceratidae. While there might be a difference of opinion as to whether these should have generic rank, they are undoubtedly groups of species deserving recognition, and seem to be sharply characteristic of horizons. These horizons may be zones, though they should not be given that rank until they are shown to have interregional significance.

Dr. Böse has enriched his work with numerous critical comparisons with all known kindred Permian ammonoids, so that in the future paleontologists will have an easier time in determining relationships and stratigraphic positions of this group. The species and genera are all fully described and beautifully illustrated.

This contribution should take rank with that of Karpinsky on the *Artinsk* fauna of the Ural Mountains, and of Gemmellaro on the Sicilian Permian, and make Texas a classic region for the study of late Paleozoic ammonoids.

James Perrin Smith

La Face de la terre. Par Ed. Suess, Traduit avec l'autorisation de l'auteur et annoté sous la direction de Emmanuel de Margerie. Tome III: 4^{e} Partie (Fin) avec un Epilogue, par P. Termier, de l'Academie des Sciences. Also, Tables générales de l'ouvrage. Paris: Librairie Armand Colin, 1918. Pp. 1361–1724 and 1–258.

An event of no little importance to geologists has been the issue of the concluding parts of *La Face de la terre,* the French edition of *Das Antlitz der Erde* by Eduard Suess, by many considered the greatest treatise upon geological science since the founding of modern geology.

The complete French edition of this great work now comprises no less than 13,437 imperial octavo pages, 12 colored plates, and 583 figures in the text. Suess's work exists complete therefore in English and French, as well as in the original German edition and the first volume has been done into Italian. The importance which attaches to the French edition lies in its great superiority over the original, and this not alone because of its better dress, but because the translator has supplied a vast amount of original material out of a mental equipment

for such work which is today unrivaled in the world. This material has been introduced in footnotes, while rendering a most faithful translation of the original text and, further, enriching the work with 487 illustrations, or more than four times the original number in the German text.

The making of this French edition of a great philosophical work has extended over twenty-five years and has involved an amount of painstaking labor such as is seldom assumed by a savant of the high scientific attainments of Dr. de Margerie, a former president of the Geological Society of France.

The initial volume of the text appeared in 1897 and was introduced by that master-mind which has contributed so much to French and especially Alpine geology, M. Marcel Bertrand; and now the concluding part is most appropriately closed after an interval of twenty-two years by an epilogue from the pen of M. Pierre Termier, likewise a profound student of those problems with which this *tour de force* especially deals. There is propriety in here translating a few lines from Bertrand's Preface and Termier's Epilogue. In the former we read:

> One of our masters said to me one day a propos of a work of one of our colleagues which had greatly interested us, "He is perhaps the one who has best comprehended Suess." This expression appeared to me to be under its simple and unpremeditated form the most striking tribute to the author of the *Antlitz der Erde*. . . . . The *Antlitz der Erde* brings together the work of an entire century. It sets forth the state of knowledge acquired about the globe which we inhabit. It shows with samples in hand that the era of groping has passed and that the grand features of the earth's face are now known to us; it determines the frame into which henceforth each new observation can take its place and acquire its full value. . . . . It [Suess's method] has been able to show the relationships and establish the connections from one limit of our hemisphere to the other, which, for example, had not before been perceived even from one boundary of France to the other. M. Suess has known how to elevate the fundamental features to a sufficient altitude to be seen above the complex details of their surroundings.

Dr. de Margerie had brought his labors upon this great work to a conclusion when the hostilities of the world-war were coming to an end with the signing of the armistice. It is altogether natural and proper therefore that M. Termier's Epilogue should take account of the new race psychology based upon revelations which have struck deep into the souls of us all, and to those of Frenchmen more than of any others. He says:

The publication of this work, the French edition of *Das Antlitz der Erde*, has been completed in mourning. The epilogue which I had been asked to write, and which formerly in happy years I had dreamt to offer to the old master as a tribute of admiration, affection and gratitude, will, alas, be neither read nor heard by him; and in penning these lines I can put into them neither the enthusiasm nor the joy of my dream, because the hour is sad and too much blood and too many tears have flowed upon the terrible way where humanity drags along.

Eduard Suess died at Vienna during the night of the 25–26 April, 1914; passed away peacefully, without suffering, painlessly, without having any presentiment of those disasters which were about to descend upon Europe. Many will agree with me in thinking that he did well to die in the care-free spring, the forerunner of a summer of massacres. Altogether good, generous, devoted to others, evidently made for sweetness and tenderness, he would have suffered atrociously to see what we have seen, to see entire peoples seized with madness, the face of the earth ravaged and blood-soaked, the hate of races which he believed abolished exasperated even so as to desire extermination; to see this impassable and indestructible barrier erected across Europe to separate the friends of yesterday, those who collaborated in the works of peace, of life, of brotherhood; those who would have forgotten their ancient frontiers . . . . and who now are enemies for how long a time—Great God! He has known nothing of these things, he has appeared to fall asleep in the quiet of his home in the heart of a city prosperous and happy, in the silence of the peaceful night, at the end of April, in this time of the year, ... Yes, in truth, the hour was favorable for men to depart and enter quietly into dissolution: he has done well to die.

It would be idle to deny that Suess has advanced hypotheses to which he adhered with the greatest tenacity, but which have not stood the test of time, such, for example, as his idea of the horst. In a biographical note published in this journal shortly after the death of Suess the reviewer wrote of the *Antlitz:*

The honest critic must frankly admit that, great as is this masterpiece of geological generalization, it suffers from two rather serious defects. Its author was almost too clever as advocate and parliamentarian and was, moreover, not without bias. With a manner altogether masterful, he could dismiss as it were with a wave of the hand important evidence which was unfavorable to maintenance of his thesis and, with equal ability, could magnify the weight of much less valuable or unimportant observations. Again, his great work suffers from a bewildering detail and an enumeration of localities too small to appear upon maps outside the original articles but upon which the conclusions are absolutely dependent, so that the reader is prevented from following the author's argument.

Termier's tribute to the distinguished translator of the *Antlitz* is well merited and may here take the place of the poor words of the reviewer. He continues:

I recall my astonishment and the admiration which I immediately conceived for the character of Emmanuel de Margerie, still unknown to me, upon that day of the year 1890 when Marcel Bertrand said to me the simple words: "De Margerie has the intention of translating the *Antlitz*, you will see that he will go to the end." Once more Marcel Bertrand has been a good prophet.

Open now the French edition alongside the German edition and compare them volume by volume, chapter by chapter. You will be amazed, not alone at the scrupulous exactitude of the translation, not alone by the reverent fidelity, truly filial, of the disciple in retaining the accent of the master and reproducing his thought even to its exact shade, but even more at the magnificent prodigality with which the disciple has enriched the work of Eduard Suess. The farther one penetrates into the work, the more this enrichment becomes manifest. In place of tiring, of exhausting himself, the translator expands his erudition and feels his enthusiasm growing, and here it is that he adds to each fact cited by the author ten other facts which complete the first and place it in the full light. So that the French edition which guards in the body of the text the moderation and the clarity of the German text, offers to its reader in addition a world of documents, notes, maps, or sketches of which each is in its proper place and supplies valuable information.

Thus you will understand the affection of Eduard Suess for Emmanuel de Margerie. I have never spoken to the master of his French translator without seeing the tears appear in his splendid eyes, where they appeared to reflect the majesty of the universe.[1]

In truth, Emmanuel de Margerie has deserved well of science. He has opened fully and definitely to all scholars of the Latin race the access to the "magnificent temple." Thanks to him into our half of the scientific world Suess's work will penetrate with greater richness and comprehensibility, and in the other half many a savant who has read *Das Antlitz der Erde*, will prefer *La Face de la terre*.

William Herbert Hobbs

Geology of Missouri. By E. B. Branson. University of Missouri Bulletin. Vol. XIX, No. 15. 1918. Pp. 172.

This bulletin gives a summary of the geological history of Missouri, with a very brief description of the principal formations and the principal

[1] The same warm affection Suess cherished for Marcel Bertrand, and the reviewer can testify that his eyes welled with tears as he referred to the darkened years which closed the career of this great French savant. It is worth our while to remember this in these days of race hatreds without parallel.

geographic changes which the state underwent in the course of its history. It is illustrated by numerous paleogeographic maps and some excellent diagrams and sections. This brief summary of the geological history of the state is very welcome to those who live beyond the confines of Missouri, as it doubtless is to many residents of the state.

One chapter deals with the life of the various geologic periods. Others deal with the minerals and rocks of the state and with its economic geology. The later chapters outline the range of industries dependent upon geologic materials, and give a summary of the value of the mineral products. The range of mineral resources is perhaps larger than most of those unfamiliar with the geology of the state have known.

R. D. S.

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VOLUME XXVII NUMBER 3

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

APRIL-MAY 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, London and Edinburgh
THE MARUZEN-KABUSHIKI-KAISHA, Tokyo, Osaka, Kyoto, Fukuoka, Sendai
THE MISSION BOOK COMPANY, Shanghai

April-May 1919 Vol. XXVII, No. 3

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit. Deliveries are not guaranteed within the war zones of Europe, nor in other countries where transportation is disturbed by conditions incident to war.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Separates, if desired, must be ordered in advance of publication. Separates of leading articles will be printed as ordered, of which 50 (without covers) will be furnished *gratis*, the actual cost of the remainder (and covers, if desired) to be paid for by the author. The actual cost may vary, and will depend upon the amount of work in remaking the pages into forms, presswork, paper, binding, etc. Separates containing half-tones may be expected to cost somewhat more, the increase depending upon the number of cuts and the amount of work required upon them.

Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

VOLUME XXVII NUMBER 3

THE

JOURNAL OF GEOLOGY

APRIL-MAY 1919

THE BUILDING OF THE COLORADO ROCKIES

ROLLIN T. CHAMBERLIN
The University of Chicago

CONTENTS

PART I

INTRODUCTION

Many phases of geology involve little more than an understanding of what has taken place at or near the surface of the earth. They can thus be studied more or less directly. A study of diastrophism, however, involves in addition a consideration of what has taken place at greater depths. The visible mountain range is but the outward expression of more deeply operating forces.

Its surficial features may be fairly well appreciated; but its deeper portions are as yet very imperfectly understood. Furthermore the visible expression is material, while the formative process is dynamic. The deeper and dynamic qualities are thus to be unraveled only indirectly by special methods.

In Chamberlin and Salisbury's *Geology*[1] a method has been given for deducing the thickness of the earth shell involved in a given case of folding. This method utilizes the principle that if the amount of crustal shortening be known and also the amount of uplift resulting from the folding, the depth of the deformed block may readily be calculated. It is first tentatively assumed that the folding process has occasioned a change of shape, but has only produced a negligible change of volume, the cubic contents of the deformed block being essentially the same after folding as before. If this assumption be allowed, the product of the original length of the section before folding times the amount of uplift resulting from the folding, will equal the amount of crustal shortening times the depth of the folded zone. Since the indications are that the increase in density and reduction in volume of the deformed mass in cases of ordinary open folding are relatively slight and can if necessary be covered by a corrective factor, this method appears to be trustworthy.

An application of these principles by a trial of this method upon the Appalachian Mountain system led to some very unexpected results.[2] The mountainous belt of central Pennsylvania having been selected for the trial, because folding is so typically displayed there, a strip across the mountains from Tyrone to Harrisburg was measured and its cross-section plotted to scale. The plotted section was then divided into six subdivisions. Applying the method above outlined, the depth of the folded zone was calculated separately for each subsection. The result was the discovery that the two shallowest sections were on the two margins of the folded region, while the deepest portion was in the middle of the range. This would indicate that the shape of the deformed

[1] II (1906), 125–26.

[2] Rollin T. Chamberlin. "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, XVIII (1910), 228–51.

Appalachian mass in central Pennsylvania was that of a triangular prism, or wedge, which apexed downward in the middle of the range. Though the wedge-shaped mass was a result quite unexpected, it did harmonize well with various theoretical considerations. In fact it not only appeared reasonable of itself, but seemed to suggest that the principles developed might well be of very general application to mountain building, and might also find some application to plateaus and continental sectors. The wedge-shaped block and wedge dynamics in deformation seemed to open up possibilities along a new line. In view of this, it seemed desirable to apply this method of inquiry to some other mountain systems. For this work the Rocky Mountains were the most available, and as a result of preliminary scouting in the summer of 1913 the section in the vicinity of the Denver and Salt Lake Railroad (Moffat Road) in northern Colorado was selected for the trial. The strip from the Great Plains near Lyons to the Grand Hogback at Glenwood Springs affords perhaps the most characteristic section which can be selected, and is at the same time readily accessible. The special field work for this cross-section was done largely in the summers of 1915 and 1916, besides which short supplementary visits were made in 1917 and 1918, including many trips to points off the section for collateral suggestions.

THE COLORADO ROCKIES

The Rocky Mountain system extends from the Endicott Range of northern Alaska southward as far as central New Mexico, where it gradually fades out. It is a belt of varying width and structure. In Alberta and British Columbia the Rocky Mountain system, according to Daly, is very definitely bounded by the Great Plains on the east and the Rocky Mountain trench on the west.[1] It is bordered on its eastern margin throughout many degrees of latitude by great overthrust faults. In its western part, though faults continue to be numerous, folding becomes more prominent.[2] Characterized thus structurally, the Rocky system continues

[1] R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Can., Memoir 38* (1912), Pl. III and p. 27.

[2] R. G. McConnell, "Report on the Geological Features of a Portion of the Rocky Mountains," *Geol. Surv., Can.*, II (1886), Part D, pp. 31 to 40.

southward nearly halfway across the state of Montana.[1] The regular, linear, faulted chain here loses its distinctiveness and identity, and gives way to an irregular group of scattered mountain clusters in west central and southwestern Montana. Many of these have resulted from igneous outbursts, and exhibit the results of vertically acting forces fully as much as horizontal thrusting. Progressing southward across Wyoming, the ranges of the Rocky group tend to come together more closely in alignment and form a more distinct, continuous chain. But the characteristic structure of the system has changed. Gentle, open folding has replaced thrust faulting as the key structure. This continues across Colorado and into New Mexico.

On many maps the western half of the state of Colorado gives the impression of a tangle of mountains which manifest but little order in arrangement. Such, however, is not the case. The Rocky Mountains enter Colorado from the north as two distinct ranges—the Front Range on the east and the Park Range to the west. Southward these two ranges gradually converge. Though the Park Range dies out in the vicinity of Buena Vista, it is replaced, *en échelon*, by the Sawatch Range. Farther south, in the neighborhood of Salida, the Sawatch chain breaks down and is replaced in turn by the Sangre de Cristo Range. In about the same latitude the Front Range dies down and is replaced south of the Arkansas River by the Wet Mountains. The convergence continues until the two groups of ranges come together near La Veta Pass, from which point southward into New Mexico the entire Rocky Mountain system comprises but a single serrate ridge—the Culebra Range, or southern Sangre de Cristo Mountains. The pattern on the map is represented somewhat approximately by the letter Y, though the two upper branches do not converge quite so rapidly as in the printed letter, and the *en échelon* arrangement of the individual ranges disturbs, to a certain extent, the smoothness of alignment (Fig. 1).

This Y includes all of the Rocky Mountain system proper, which is essentially a folded system in Colorado. West of the

[1] Bailey Willis, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. of Amer.*, XIII (1902), 305–52; F. H. H. Calhoun, *U.S. Geol. Survey, Prof. Paper 50* (1906), pp. 9–10.

Rockies proper are several scattered mountain groups, such as the San Juan Mountains, Elk Mountains, West Elk Mountains, and Flattop Mountains, which mark spots of excessive Tertiary vulcanism. Structurally they are quite distinct from the folded Rockies proper, and occur as isolated groups in the midst of comparatively undisturbed, flat-lying sedimentary rocks. There are

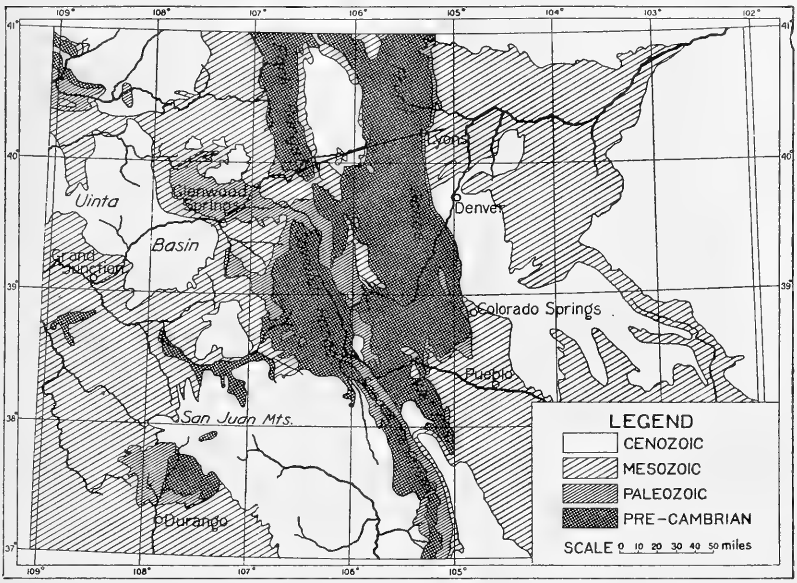

Fig. 1.—Geologic map of Colorado (after R. D. George). The darkly shaded pre-Cambrian areas delineate rather closely the pattern of the Rocky Mountains within Colorado. The ranges converge southward in *en échelon* arrangement roughly suggesting the letter Y.

also some local domelike upwarps in the western part of the state. These local upwarps and the isolated groups genetically related to Tertiary vulcanism should be sharply differentiated from the Rocky Mountains proper—the folded range. The history of the impressive San Juan group has been worked out in detail by Cross,[1] Atwood,[2] and others.

[1] Whitman Cross, *U.S. Geol. Survey, Geol. Atlas,* Needle Mountains, Rico, Silverton, Telluride, and other folios.

[2] W. W. Atwood, "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Survey, Prof. Paper 95-B* (1915), pp. 22–24.

The differentiation of Colorado's mountains into the Rocky System proper and the subordinate scattered groups mostly associated with Tertiary vulcanism is apparent on either the topographic or the geologic map of the state.[1] The Rocky Mountain Y has a pre-Cambrian granite backbone throughout nearly the whole of its extent. In fact, the pre-Cambrian areas of Colorado, except for a large area of igneous and metamorphic rocks south of the Gunnison River, delineate very well the pattern of the Rocky Mountains. The southward converging of these folded ranges of old rocks, which taper into a single mountain ridge, appeared significant and possibly suggestive of the type of deformation which has taken place. It seemed to imply some sort of wedge dynamics below.

HISTORY OF THE MAIN RANGE

The present Rockies are not the first mountain system developed within the area of Colorado. After a flooding of the region by early Pennsylvanian seas there arose, before the close of the Pennsylvanian period, an ancestral Rocky Mountain range.[2] The elevation of these ancient Rockies has been assigned by Lee "to the period of diastrophism usually called the Appalachian Revolution which wrought world-wide changes in climate, geography, and biology."[3] But Lee recognizes that these ancient Rockies were probably uplifted before the Permian, because sediments derived from the erosion of this ancestral range have formed the Permian beds of the neighborhood. Still further, if the present tendency to place the Fountain sandstone and its equivalents within the Pennsylvanian[4] be correct, this growth of early Rockies must have taken place during the Pennsylvanian, as that period is now defined, since the sediments which made the Fountain sandstone came from the destruction of the newly

[1] The Topographic Map of Colorado. R. D. George, 1913.

[2] Willis T. Lee, "Early Mesozoic Physiography of the Southern Rocky Mountains," *Smithsonian Misc. Coll.*, LXIX, No. 4 (1918), pp. 5-7.

[3] *Ibid.*, p. 6.

[4] R. M. Butters, "Permian or 'Permo-Carboniferous' of the Eastern Foothills of the Rocky Mountains in Colorado," *Colo. Geol. Survey, Bull. 5* (1913), Part 2, pp. 65-94.

uplifted range. More exact determination of the age of this diastrophism must await closer correlation of these lower Red Beds. But one may well wonder whether this ancestral Rocky Mountain building, which seems to correspond in time with a prominent period of folding in the Arbuckle Mountains of Oklahoma, may not prove to have been closely related to the mid-Pennsylvanian Hercynian orogenic disturbance recognized by Baker and Bowman in the Trans-Pecos region of Texas.[1] On the other hand, the Appalachian diastrophism would seem to have come after a portion at least of the Permian, if the Dunkard beds included in the Appalachian folded series are correctly referred, as is commonly done, to the Permian.

It is not sufficiently clearly recognized by geologists that the diastrophism marking the closing stages of the Paleozoic was a double diastrophism,[2] comprising an essentially world-wide Hercynian orogenic disturbance—the Westphalo-Carbonide movement between the Westphalian and the Stephanian—and a more local Appalachian disturbance, the Permo-Carbonide movement which came after a portion at least of the Permian. It was the earlier, or Westphalo-Carbonide, movement that inaugurated those profound climatic changes which are recorded in widespread evidences of vigorous glaciation within the tropics, in the astonishingly wide prevalence of Red Beds the world over, and which are reflected in turn in great changes in life, and which, in view of the dominating character of these changes and their great significance from many standpoints, may perhaps not unfittingly be chosen as the dividing line between the Paleozoic and the Mesozoic.

Lee states that in few places in the Rocky Mountains can a line of separation be drawn between the Permian and Triassic rocks, while there is a much greater break in sedimentation between the Pennsylvanian limestone and the Permian Red Beds.[3] During the later Pennsylvanian and Permian periods detritus from the

[1] C. L. Baker and W. F. Bowman, "Geologic Exploration of the Southern Front Range of Trans-Pecos, Texas," *Univ. of Texas, Bull. No. 1753* (1917), pp. 107–12.

[2] Rollin T. Chamberlin, "Periodicity of Paleozoic Orogenic Movements," *Jour. Geol.*, XXII (1914), 334–45.

[3] Willis T. Lee, *op. cit.*, p. 7.

newly uplifted mountains was deposited nearby and formed the now prominent non-marine Red Beds. Erosion of the mountains continued through the Triassic and part of the Jurassic, approaching peneplanation before the close of the Jurassic and preparing the way for a marine invasion in Upper Jurassic times.[1] The submergence did not last long, and upon the graded plain abandoned by the sea and the peneplaned area surrounding it the streams of early Comanchean time spread out the sediments of the Morrison formation.[2]

The Cretaceous period was a time of very extensive marine sedimentation in the Rocky Mountain region. Lee has brought out the fact that the Dakota sandstone, and probably also the overlying marine Cretaceous formations, formerly extended uninterruptedly over the areas now occupied by the Colorado Rockies.[3] These Cretaceous beds mark the last great marine invasion of the interior of North America and are represented by a thick stratigraphic column. In waning Cretaceous times the seas shoaled and withdrew, causing marine sedimentation to give way to terrestrial deposits with included coal beds.

Laramide diastrophism.—The Cretaceous period was the long quiet before the storm. At its close the growing stresses within the earth sought relief in folding movements. These were of a pulsatory nature, for at least two distinct periods of folding have been distinguished. In northern Colorado the first of these followed the deposition of the Laramie formation of the Denver Basin. But in southern Colorado no folded formation so late as this has been preserved, owing to the greater erosion there in the interval between the folding and the deposition of the basal Eocene. In that region the last formation affected by the Laramide disturbance which has escaped removal is the Vermejo formation of the Mon-

[1] *Ibid.*, pp. 7–12 and 24–41; also W. N. Logan, "A North American Epicontinental Sea of Jurassic Age," *Jour. Geol.*, VIII (1900), 242–73.

[2] See C. C. Mook, "A Study of the Morrison Formation," *Ann. New York Acad. Sci.*, XXVII (1916), 31–191.

[3] Willis T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U.S. Geol. Survey, Prof. Paper 95-C* (1915), pp. 27–58.

tana group.[1] The exact extent of this diastrophic movement has not yet been satisfactorily determined for the Colorado region, principally for the reason that contacts between the Cretaceous and early Eocene within the folded portion of the range are few and very unsatisfactory, owing to the great amount of erosion which has taken place there. Folded or faulted Cretaceous beds overlain by less disturbed early Eocene strata are not found at many places in Colorado. In Wyoming, however, there are numerous sections in which the Adaville formation (upper Montana and lower Laramie) shows profound folding and faulting followed by extensive erosion before the deposition of the Evanston (early Eocene) beds, which lie in strong discord across the truncated edges of the Mesozoic strata.[2]

In Colorado the Laramide upfolding of the Rockies resulted in a rapid erosion of the newly risen mountains and the accumulation of the Dawson arkose and the Arapahoe conglomerate near Colorado Springs and Denver, and the development of the Raton formation farther south. Some idea of the extent of the upfolding may perhaps be obtained from the amount of erosion which immediately followed. Cross has estimated that post-Laramie erosion had already, in Arapahoe times, removed from portions of the folded belt west of Denver the great total of 14,000 feet of strata, since pebbles derived from various geological horizons down as far as the Trias are found in the Arapahoe beds.[3] In the same way Lee has estimated that the conglomerate at the base of the Raton formation in southern Colorado is stratigraphically more than 18,000 feet above the crystalline and metamorphic rocks that furnished most of the pebbles found in it.[4] Lee, however, recognizes

[1] Willis T. Lee and F. H. Knowlton, "Geology and Paleontology of the Raton Mesa and Other Regions in Colorado and New Mexico," *U.S. Geol. Survey, Prof. Paper 101* (1917), p. 64.

[2] A. C. Veatch and A. R. Schultz, "Geography and Geology of a Portion of Southwestern Wyoming," *U.S. Geol. Survey, Prof. Paper 56* (1907), Pl. IV; A. R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *U.S. Geol. Survey, Bull. 543* (1914), Pl. III.

[3] Whitman Cross, "Geology of the Denver B asin in Colorado," *U.S. Geol. Survey, Monograph 27* (1896), p. 207.

[4] W. T. Lee, *U.S. Geol. Survey, Prof. Paper 101* (1917), p. 59.

that it is not known that the older sedimentary formations were conformable and once extended continuously over the now uplifted area, but states that in any case the Cretaceous sedimentary rocks are conformable throughout, and in order that pebbles of sandstone from the Dakota and the still older Red Beds could be incorporated in the conglomerate there must have been differential uplift and erosion of more than 4,000 feet. Though making this very safe and modest estimate, Lee has expressed his belief that the actual erosion was probably very much greater than 4,000 feet. An estimate upon the Dawson arkose would probably be of similar import.

Above the Arapahoe in the Denver Basin is the Denver formation, whose composition is of much significance. According to Cross the material of the Denver beds, which must have come from the highlands to the west, may be classed as débris partly from the Archean, partly from sedimentary rocks, and partly from andesitic eruptive rocks.[1] The Arapahoe strata contain little or no fragmental material derived from eruptive rocks, while on the contrary the lowest 900 feet of the overlying Denver beds are composed largely of andesitic materials and contain very little granitic or sedimentary débris. Cross says: "The andesitic masses which furnished the materials for the lower part of the Denver sediments were so situated as to effectively prevent the access of all Archean and sedimentary débris to the sea of that epoch. That is to say, the Archean and sedimentary rocks in the mountainous area drained by the tributaries of the Denver sea must have been covered by andesitic lava flows so that no material other than the eruptive débris could appear in the Denver sediments, from this, the prominent source, until erosion had laid bare, here and there, small areas of granite, of gneiss, or of sandstone."

More direct evidence of these floods of andesite, the postulated source of much of the material of the Denver sediments, has been found in Middle Park, where there is a thick formation of andesitic breccias and tuffs with conglomerate and sandstone resting unconformably upon the Cretaceous, and which is comparable to the

[1] Whitman Cross, *op. cit.*, pp. 199–206.

Denver formation in lithological character and in its fossil plants.[1] Along the Grand River, in the line of the section which was measured as the basis for this present study of the Rocky Mountain deformation, the Middle Park formation outcrops continously for a distance of $4\frac{3}{4}$ miles. Its structure, as was first noted in the very excellent description by Marvine,[2] is basin-like. On the eastern limb of the syncline the steeply inclined, westerly dipping beds of the basal portion of this formation, form the conspicuous mountain ridge through which the Grand River flows at Windy Gap, $3\frac{1}{2}$ miles northwest of Granby. Westward toward the middle of the basin the dip rapidly lessens, and for several miles is not far from horizontal, but farther west the lower beds of the volcanic series emerge again about 2 miles east of Hot Sulphur Springs.

At Windy Gap the Middle Park formation consists of a series of breccias, tuffs, conglomerates, and sandstones dominantly of andesitic derivation. In the lower portion there are several hundred feet of coarse breccia containing many cobbles and angular fragments of andesite up to six inches in diameter. Higher up in the series the material becomes finer, and rounding by water action becomes more prominent. Within the first five hundred feet of the formation no evidence of granitic materials was observed. The pre-Laramide formations at this stage supplied very little detritus to be mixed in with the andesitic derivatives. But in time the lithological character of the accumulation underwent a change as new sources of material became available. About 1,000 feet stratigraphically above the base of the formation some very striking conglomerates appear in the hills immediately west of the Windy Gap Ridge. Well-rounded cobbles of four or five inches represent the average coarseness, though bowlders of a foot or more in diameter are not difficult to find. These cobbles are of granitic rocks and various fine-grained porphyries, particularly grayish-green andesite. The only available source for the granites is the

[1] Whitman Cross, "The Post-Laramie Beds of Middle Park, Colorado," *Proc. Colo. Sci. Soc.*, IV (1891–93), 192–214.

[2] A. R. Marvine, "Report on Middle Park," *U.S. Geol. and Geog. Survey of Colorado* (Hayden), 1873, pp. 154–92.

pre-Cambrian complex, while the porphyries were as obviously derived from the flows of the Middle Park formation itself. The old granites and the Tertiary effusives are in nearly equal proportions. Above this conglomerate for another thousand feet are various arkosic sandstones and coarse conglomerates whose material has been derived from both the old granites and the young andesites. Pebbles of white and purplish vitreous quartzite are conspicuous in places.

The import of this formation is that, either accompanying a late stage of the post-Laramie folding or soon after it, there were extensive outbursts of andesite in this portion of the Colorado Rockies. These flows were either so vast or else were so located relative to the basins where sediments accumulated, that they furnished a very large part of the detritus which made up the lower portion of the Middle Park formation, as urged by Cross, while the Archean granite contributed practically nothing. But later, after these volcanics had suffered much erosion, or else there had occurred further uplifting along the granite core of the range, or both, the granite areas supplied much coarse pebble and cobble material to the sediments which were accumulating in this basin.

Early Tertiary folding.—Since deposition this Middle Park formation has suffered a period of folding which has accentuated the structural basin by causing the basal volcanics on the eastern margin of the syncline to dip westward at angles of 50°–60° and the same series on the western margin to dip eastward at angles up to 30°. The upper beds of the formation exposed in the middle of the syncline possess only very gentle undulations which cause them to depart but little from a horizontal position.

The time of the folding movement which disturbed these beds was not closely determined in this present study. In any case it was post-Middle Park and pre-Uinta, for after the folding a long period of denudation had greatly changed the region before the beds classed as Uinta were laid down. It is possible that this is to be correlated with a prominent folding period which has been recognized in the mountains of Wyoming, and which can be more closely timed. There the folding and faulting occurred between the Fowkes formation of the Lower Wasatch and the Knight formation

of the Upper Wasatch, and is represented, according to Veatch, by a break which amounts to perhaps 5,000 feet of strata.[1] But the older, post-Laramie break amounts to over 20,000 feet, and Veatch has expressed the opinion that the folding following the Lower Wasatch should perhaps be regarded as of much less relative significance than this comparison of figures might indicate, because the movements of the second disturbance were along the lines of weakness produced by the first. As to correlation, Veatch is conservative, placing the 6,000 feet of strata between these two breaks in the debatable ground between the known Cretaceous and Tertiary.

Along the western margin of the Rocky Mountain belt in the Colorado section here studied, the Grand Hogback upturn involves the Wasatch beds as fully as the Cretaceous. This may be observed to the west of Glenwood Springs, both north and south of the Grand River. At Piceance Gap to the northwest both the Wasatch and Green River beds are included in the monoclinal fold according to Gale.[2] Farther west in the Uinta Basin of Utah the Wasatch has been folded with the Cretaceous.[3] Whether this flexing on the western borders of the Rocky belt is to be correlated with the Middle Park folding within the range is uncertain. Irrespective of this it is peculiar in manifesting certain characteristics of basin-like subsidence and downwarping.

R. C. Hills has described this early Tertiary folding exhibited in certain portions of the Sangre de Cristo Range as post-Bridger, because the Huerfano beds were involved.[4] To this period of folding he has also assigned the flexing of the Grand Hogback, as well as rather widespread folding on the east flank of the front range.[5] Hills is the authority for the belief that the post-Bridger folding

[1] A. C. Veatch, *U.S. Geol. Survey, Prof. Paper 56 (1907)*, p. 75.

[2] Hoyt S. Gale, "Coal Fields of Northwestern Colorado and Northeastern Utah," *U.S. Geol. Survey, Bull. 415* (1910), Pl. XIII.

[3] C. T. Lupton, "The Blacktail Mountain Coal Field, Wasatch County, Utah," *U.S. Geol. Survey, Bull. 471* (1912), Pl. LXII.

[4] R. C. Hills, *U. S. Geol. Survey Geol. Atlas, Walsenberg Folio,* No. 68 (1900) pp. 2–3.

[5] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), 408–19.

in Colorado was nearly as widespread and equally as intense as the post-Laramie folding.[1] It followed very closely the older Laramie lines of flexure.

The post-Middle Park folding was followed by a long period of erosion in the Colorado Front Range. Erosion in fact must have been steadily at work on the main anticlines of the Colorado Rockies since their arching in the Laramide diastrophism. This long continued denudation greatly reduced the country, as is known from the fact that beds regarded as Uinta in age[2] were laid down directly upon the Archean granite over wide areas in the Grand River region of Grand County. The broad valleys and basins of the region no doubt received deep fillings of detrital material, as the country was brought toward a common level by degradation of the higher areas and aggradation of the lower. The Upper Eocene beds thus deposited exhibit in places an appreciable departure from horizontality, giving rise to a slight waviness in structure, but they seem to have suffered no pronounced folding. This warping of the Upper Eocene beds suggests that in this region there was a mild expression of the mid-Tertiary diastrophism which developed more strongly near the Pacific Coast and elsewhere.

Peneplanation.—After one or more cycles of erosion of whose details little is known, the granite ranges became an imperfect plain, above which unreduced areas remained as scattered monadnocks from 500 to 2,500 feet in height.[3] This peneplain, if such an imperfectly reduced area may be designated by that term, must have extended throughout the region of the Colorado Front Range, for remnants of it are still preserved at many points in different parts of the range. In the neighborhood of the Lyons-Grand River section, whose study constitutes the basis for the investigation in hand, these flats form conspicuous portions of the continental divide in Flattop Mountain and some of its immediate neighbors in Rocky Mountain National Park (Fig. 2). The name Flattop is correctly descriptive of an extensive flattish portion

[1] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), p. 443.

[2] Geologic Map of Colorado. R. D. George, 1913.

[3] W. M. Davis, "The Colorado Front Range," *Ann. Assoc. Am. Geog.*, I (1911), 31.

of the divide in a region of steep-sided peaks and precipitous cirque walls. The bench mark on this summit flat records an elevation of 12,364 feet. Views from the nearby peaks give the observer an excellent idea of this old peneplain. South of the Lyons-Grand River section more of the peneplain is still preserved on the continental divide. The crest of the range from the neighborhood

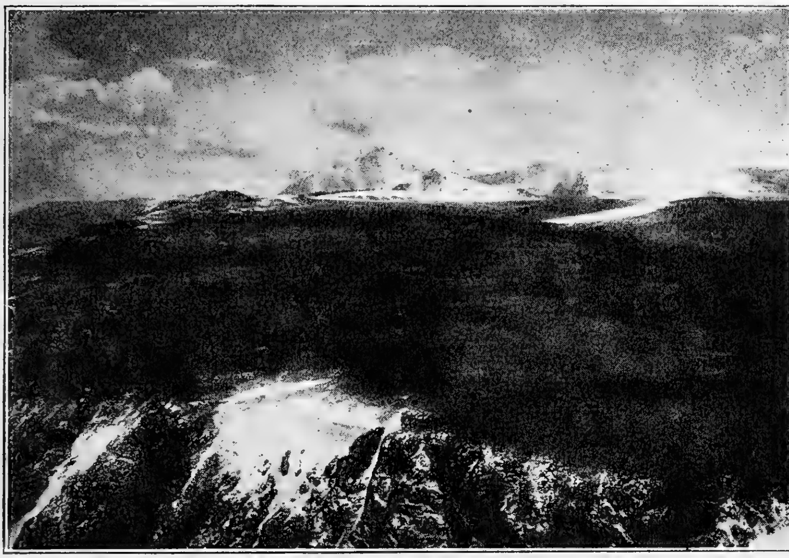

FIG. 2.—The peneplain on the continental divide. Looking southeast across Flattop Mountain (12,364 feet) to Long's Peak, a rugged peak carved from an unreduced remnant rising above the peneplain level. In the immediate foreground are the upper cirque walls of Spruce Canyon. Several other steep-walled cirques head back into Flattop but are barely visible in this view.

of Arapahoe Peak to James Peak, when viewed from the Windy Gap Ridge west of Granby, presents an almost horizontal skyline whose elevation is shown by the map of the Central City quadrangle to be very close to 12,000 feet. Continuing the vision to the south of the monadnock group comprising James Peak, Mt. Eva, and Mt. Flora, the eye is again impressed by the level sky line which extends onward for many miles with little departure from the 12,000 foot elevation.

The age of this peneplain was not determined. No ready means of dating it was found in the time at disposal, and exhaustive search was not felt to be vital to the immediate problem in hand, though admittedly very important in the history of the range and that of the general region. Perhaps something may be learned from a comparison with more favorably situated peneplains in adjoining states. The pronounced peneplain upon the Wind River Range of Wyoming has been assigned to the middle of the Miocene by C. L. Baker.[1] Baker believes that this peneplanation was interrupted, probably later in the Miocene, by an uplift, both regional and orogenic, along the lines of the earlier Laramide movement. Westgate and Branson, however, did not feel justified in dating the peneplain more closely than mid-Tertiary.[2] Blackwelder, on the other hand, believes that the Wind River summit peneplain is of Pliocene age, for which he gives a well considered argument.[3]

In the Laramie region of southeastern Wyoming, Blackwelder has described Pole Mountain and the Medicine Bow plateau surface as remnants of a peneplain developed by the Eocene cycle of denudation, while the Sherman peneplain, at somewhat lower elevation, represents in his opinion a Pliocene date.[4] These two erosion levels, if such they be, are not far apart near the Wyoming-Colorado line, indicating that but little uplift took place between these stages; but southward in the Front Range of Colorado the relief of the country becomes steadily greater. In the Long's Peak region extensive flats are found east of the main range in the neighborhood of 8,000 feet, which is not far from the Sherman level in the Sherman quadrangle, but the summit peneplain on the continental divide is here at an altitude of approximately 12,000 feet. The Great Plains abut the foothills in the Sherman region at an elevation of about 7,000 feet, ignoring the

[1] Charles Laurence Baker, "Notes on the Cenozoic History of Central Wyoming," *Bull. Geol. Soc. Amer.*, XXIII (1912), 73.

[2] L. G. Westgate and E. B. Branson, "The Later Cenozoic History of the Wind River Mountains, Wyoming," *Jour. Geol.*, XXI (1913), 144–47.

[3] Eliot Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, XXIII (1915), 193–207.

[4] Eliot Blackwelder, "Cenozoic History of the Laramie Region," *Jour. Geol.*, XVII (1909), 429–44.

river valleys which have cut well below this level; east of Long's Peak the plains have an elevation of only 5,000 feet above the sea. The greater elevation of the Front Range in Colorado is the result of greater upbowing of the old peneplain surface in that latitude.

On the Sherman (Wyo.) sheet close to the Wyoming-Colorado line, the Sherman peneplain level is in the neighborhood of 7,700 feet above the sea. On the Livermore (Colo.) sheet next south the plain rises from about 7,000 near the sedimentary hogbacks to 8,000 feet at the west margin of the sheet. On the Mt. Olympus sheet next south the general elevation of the plain is not very different, but on the Boulder sheet adjoining Mt. Olympus on the south the plain rises from 6,500 feet elevation near the city of Boulder to approximately 9,000 feet at the west margin of the sheet near the mining camp of Ward. While there may well be some minor levels included, these elevations constitute a very evident erosion plain which slopes toward the east. The slant of the plain becomes progressively steeper as it is followed southward from Sherman, Wyoming, to Boulder, Colorado, indicating a greater upwarp of the range in the latitude of Boulder.

Davis considered this old erosion plain to have been once continuous with the so-called summit peneplain whose remnants are today seen on the continental divide at an elevation of 12,000 feet.[1] If so, it would mean that the inclination of the plain becomes greater as it nears the divide. It is natural enough that there should have been sharper tilting along the axis of the range. In the region crossed by my section, however, the evidence did not seem to be altogether conclusive. There may be two plains representing different cycles. If so, this would suggest some upwarping between and would have a bearing upon the age of the summit peneplain. But if, on the other hand, the summit plain and the lower plain to the east are truly parts of the same surface of denudation, the rather obvious recency of the latter would indicate that the summit peneplain is of late Tertiary age. The erosion plain extending from Allen's Park and Ward to the foothills near Boulder must clearly be as late as the Pliocene.

[1] W. M. Davis, *op. cit.*, p. 31 and Fig. B2, pp. 76–77.

West of the continental divide along the line of the Grand River section, remnants of a former surface of little relief are observed at various points. In Pliocene times this region, if not brought to the condition of a true peneplain, was at least greatly reduced and many extensive flattish areas developed. Preserved portions of these are seen today on the western uplands of the section at elevations for the most part between 9,000 and 10,000 feet. The Lyons-Grand River cross-section given later in this paper seems, however, to belie this statement, but that is because the drawn section closely follows the course of the Grand River and only in a few places does it rise to the upland peneplain level.

Upbowing.—Since the formation of this late Tertiary peneplain, it has been bowed upward along an axis which corresponds approximately with the present crest of the Front Range. General uplift involving some little warp also affected the region west of the Front Range and accentuated the height of several of the ranges. The movement in the Front Range was a gentle tilting in the latitude of Long's Peak, though in the foothills it may have been accompanied by normal faulting. Farther south, in the vicinity of Castle Rock and Colorado Springs, Richardson's sections of the Front Range foothills show the Dawson arkose of the early Eocene to be steeply inclined, and cut by a set of normal faults, which are there an important part of the foothill structure.[1] Finlay has placed this period of disturbance within the Pliocene Period.[2]

This uplift has given the Front Range much of its present elevation above the Great Plains to the east. Streams rejuvenated by the uplift have since carved deep canyons, which head far back in the high level plain. Leading back from the plains to the open uplands of Estes Park and Allen's Park, where roads are possible in almost any direction, are the wonderful scenic canyons of the Thompson River and St. Vrain Creek, which are young in the present cycle of erosion. On the west side of the continental

[1] G. B. Richardson, *U.S. Geol. Survey, Geol. Atlas, Castle Rock Folio*, No. 198 (1915), pp. 10–11.

[2] George I. Finlay, *U.S. Geol. Survey, Geol. Atlas, Colorado Springs Folio*, No. 203 (1916), pp. 13–14.

divide the Grand River sweeps swiftly through the beautiful Byers, Gore, and Grand River canyons on its way westward, showing that, while the extent of the uplift varies from place to place, the Rocky Mountain belt in this latitude was bowed up throughout its full width. These are among the finest canyons in Colorado and through their high, rugged walls they testify to the

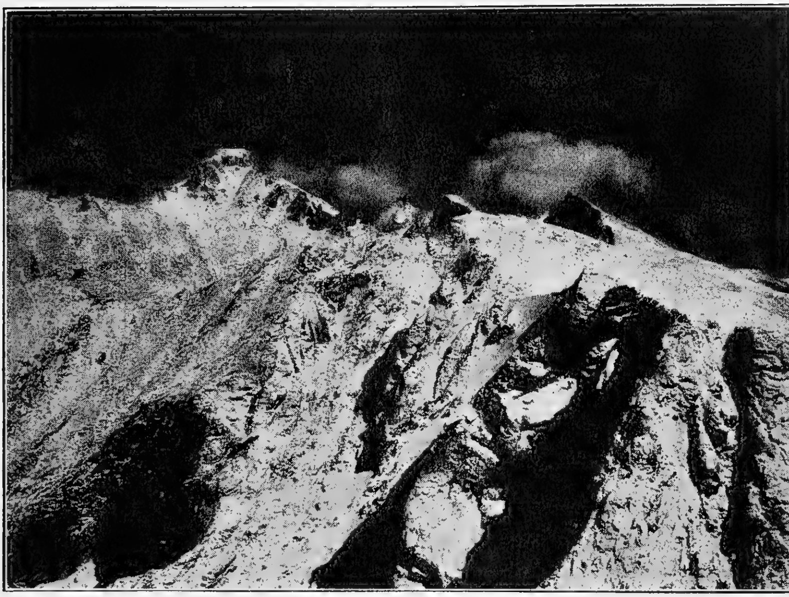

Fig. 3.—Rugged mountains sculptured from a smooth-sloped monadnock rising above the peneplain on the continental divide. Long's Peak (14,255 feet) from Taylor Peak (13,150 feet). Remnants of the smooth monadnock surface are seen on the right-hand side of the photograph in McHenry's Peak and Chief's Head. This surface was seemingly once continuous with the flat summit of Long's Peak. Glaciers stoping backward have cut profound cirques into the old surface.

extent and comparative recency of the uplift which has renewed the cutting power of the Grand River. Increased erosion on the softer sedimentary strata east of the Front Range granite area has lowered the Great Plains immediately adjacent to the foothills, thus further uncovering and sculpturing into hogbacks the more resistant beds of the steeply upturned sedimentary series of the foothill belt. The map of the Livermore Quadrangle suggests that there were

at least two distinct stages in this process. Since the weaker strata of the plains reached a stage of advanced old age, two episodes of erosion have left their impress there, according to the studies of Davis.[1]

Quaternary glaciation has also greatly modified the details of the mountainous belt. By the cirquing and stoping process, serrate peaks and sharp ridges have been carved and sculptured out of the rounded monadnocks and remnants of the summit peneplain (Fig. 3). Rounded U-shaped valleys with capacious cirques testify to the potency of glacial erosion in the adjoining valleys.

[1] W. M. Davis, *op. cit.*, p. 31. See also N. M. Fenneman, "Geology of the Boulder District, Colorado," *U.S. Geol. Survey, Bull. 265* (1905), Fig. 1 and Pl. IIIA.

[*To be continued*]

NOTES ON THE GEOLOGY OF GEORGIA

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Atlanta, Georgia

ARCHEAN SYSTEM

The geological history of Georgia begins with the ancient Crystalline rocks, the greater part of which are supposed to be of Archean age. These rocks form a northeast-southwest belt about 125 miles wide traversing the northern part of the state and are a part of the great belt of ancient Crystallines extending from northeastern New York to eastern Alabama (Fig. 1). The areal extent in Georgia is about 15,000 square miles, or approximately one-fourth of the state. They occupy all of the physiographic division known as the Piedmont Plateau, and a part of the Appalachian Mountain division. To the northwest they are limited by the metamorphic Cambrian rocks and to the south by the Tertiary. The latter boundary is sharp and distinct, while the former is ill-defined. These rocks are here described under the following names: Carolina gneiss, Roan gneiss, and granites.

The *Carolina gneiss*, so called from its wide distribution in the Carolinas, where it has been studied by Keith and others, is the prevailing rock of the ancient Crystallines of Georgia (Fig. 2). Broadly speaking, the formation may be correlated with the Baltimore gneisses of Maryland and the Stanford and Fordham gneisses of New York.

The most abundant, widespread, and typical rocks of the Carolina formation are schists, largely micaceous and garnetiferous, and biotite gneiss. In addition there occur in more or less restricted areas graphitic schist, quartzitic schist, and schistose conglomerate. The most persistent character of these rocks is the schistose and bended structure due to the segregation of the component minerals along definite lines. They are the oldest rocks of the state and may be considered the country rock into which the Roan gneiss and

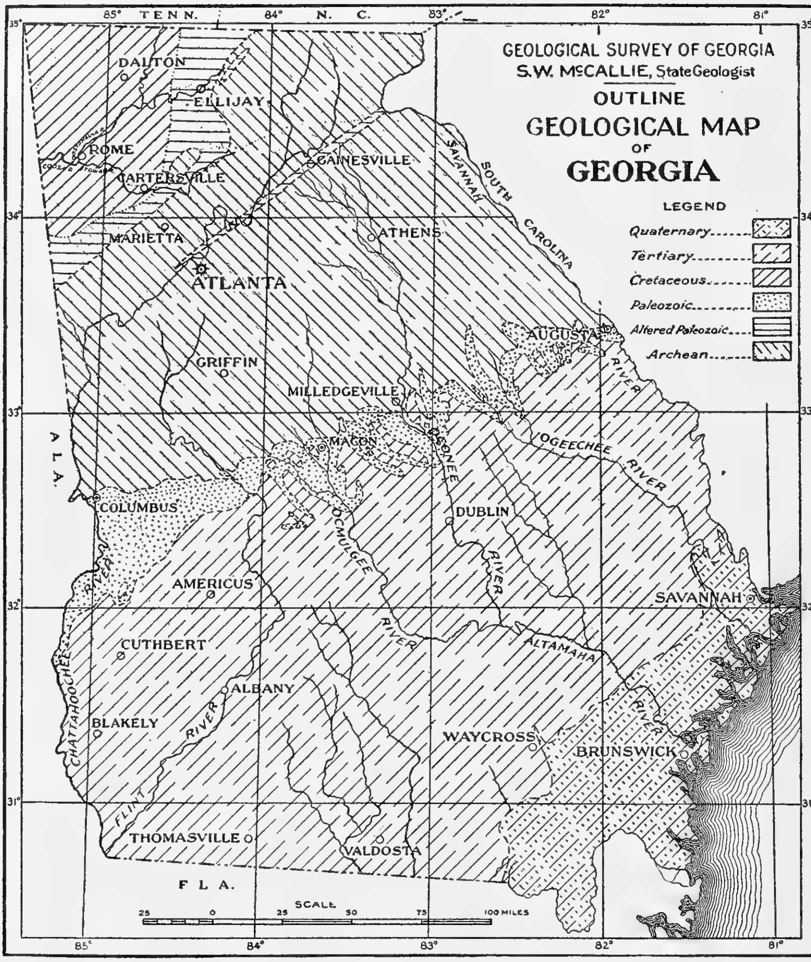
GEOLOGICAL SURVEY OF GEORGIA
S.W. McCALLIE, State Geologist
OUTLINE
GEOLOGICAL MAP
OF
GEORGIA
LEGEND
Quaternary
Tertiary
Cretaceous
Paleozoic
Altered Paleozoic
Archean
TENN.
N. C.
SOUTH CAROLINA
ALA.
FLA.
DALTON
ELLIJAY
ROME
CARTERSVILLE
MARIETTA
ATLANTA
GAINESVILLE
ATHENS
GRIFFIN
MILLEDGEVILLE
AUGUSTA
MACON
COLUMBUS
DUBLIN
AMERICUS
SAVANNAH
CUTHBERT
ALBANY
BLAKELY
WAYCROSS
BRUNSWICK
THOMASVILLE
VALDOSTA
SAVANNAH RIVER
OGEECHEE RIVER
OCONEE
OCMULGEE RIVER
ALTAMAHA RIVER
CHATTAHOOCHEE RIVER
FLINT RIVER
SCALE
100 MILES
85°
84°
83°
82°
81°
35°
34°
33°
32°
31°

FIG. 1

COLUMNAR SECTION
ALTERED PALEOZOIC AND ARCHEAN ROCKS OF GEORGIA

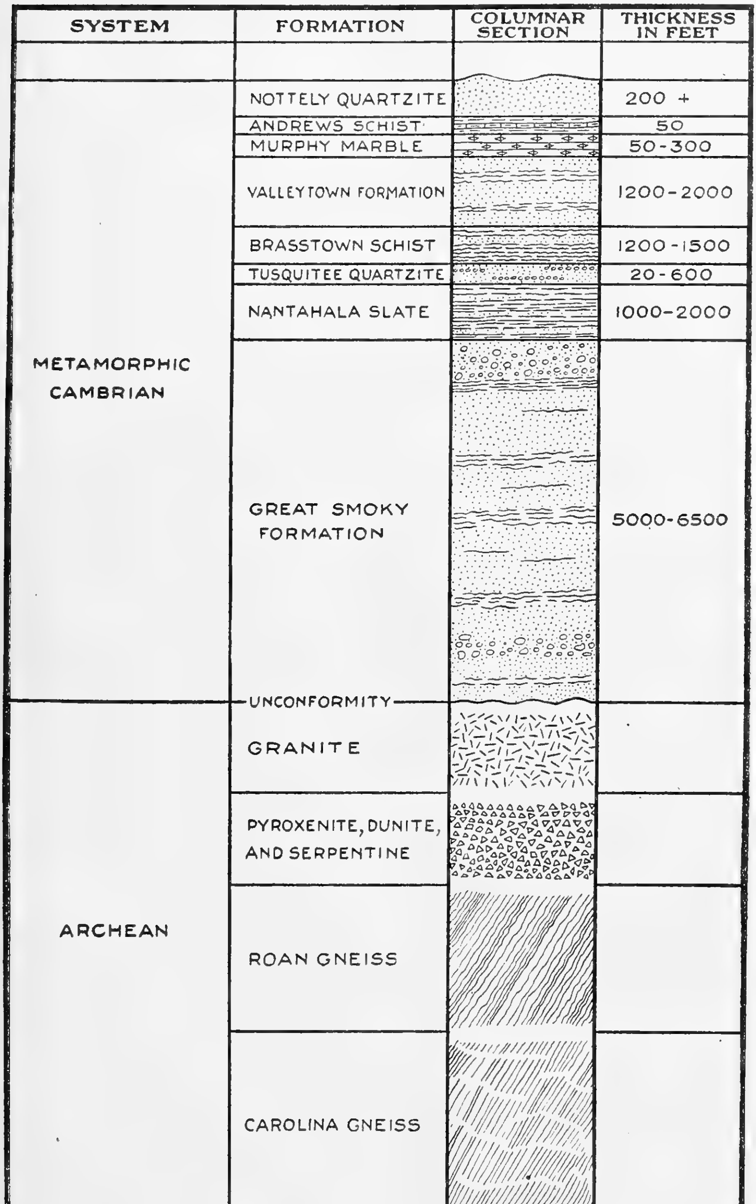

Fig. 2

granites have been intruded. The series is supposed to be largely of igneous origin, though sediments undoubtedly occur in certain localities, as shown by the graphitic schist, quartzitic schist, and schistose conglomerate.

The *Roan gneiss* is a series of basic igneous rocks including hornblende schist, hornblende gneiss, and schistose diorite. These rocks occur in belts varying from a few feet to hundreds of rods in width and often cut the Carolina gneiss, into which they have been intruded at rather high angles. Less abundant and only locally developed are pyroxenites, dunites, and serpentine belonging to the same series.

The *granites* are widely distributed and in places cover areas of many square miles. They are prevailingly biotitic and generally show gneissic structure. In age they are supposed to be largely pre-Cambrian, though the more massive varieties, such as Stone Mountain near Atlanta, are probably younger. The granites unquestionably represent two or more periods of intrusion.

CAMBRIAN SYSTEM

ALTERED CAMBRIAN

The Cambrian system is divided into the altered and unaltered Cambrian. The altered or metamorphic Cambrian rocks, so far as known, are mainly confined to an irregular belt, varying in width from eight to twenty-five miles, in the northwestern part of the state. The belt lies immediately west of the Archean rocks and embraces in its northern extension a greater part of the Appalachian Mountain physiographic division of the state. These rocks belong to the Ocoee group of Safford and were long regarded as of Algonkian age. However, fossils of Lower Cambrian age are found as far down as the middle of this group of strata in Tennessee and North Carolina, and the strata below the fossil-bearing beds are conformable and not materially different in character. In addition to this main belt there is a narrow belt known as the Brevard schist entering the state from South Carolina northeast of Gainesville and stopping about five miles west of Atlanta. It seems quite probable that the metamorphic Cambrian originally overlay the Crystallines as far east as Atlanta and possibly beyond.

This group of altered sediments has been studied in detail only in one section of the state, namely, the area covered by the *Ellijay Folio*. In that locality the rocks have been described by La Forge and Phalen under the following formation names: (1) Great Smoky formation, (2) Nantahala slate, (3) Tusquitee quartzite, (4) Brasstown schist, (5) Valleytown formation, (6) Murphy marble, (7) Andrews schist, and (8) Nottely quartzite.

The *Great Smoky formation*, in the Ellijay quadrangle along its eastern margin, lies upon the Carolina gneiss, although the immediate contact is difficult to define, as in that section the latter is made up largely of graywacke and conglomerate, which are very similar in lithological character to the base of the Great Smoky. The formation consists of a great thickness of conglomerate, graywacke, sandstone, quartzite, slate, mica schist, garnet schist, and staurolite schist. The conglomeratic phase is best developed to the east and north, while to the west and south the mica schist, quartzite schist, and slates prevail. The Great Smoky formation is a part of Safford's Ocoee series and has been provisionally correlated with the Cochran and the Thunderhead conglomerates of Tennessee and North Carolina. West of the Ellijay quadrangle and below the Great Smoky formation occur considerable areas of the Wilhite slate and the Gilmer formation, but their detailed structure and relations have not yet been worked out.

The *Nantahala slate*, near the Georgia-North Carolina line, includes principally blackish and dark-gray slates, though white quartzite and staurolitic schist are also more or less plentiful. Farther south in the vicinity of Ellijay and beyond, the formation is mainly graphitic schist with but few siliceous beds. Its distribution is confined to the eastern margin of the metamorphic area, where it forms narrow belts rarely over a mile in width.

The *Tusquitee quartzite*, which is apparently confined to the Ellijay quadrangle, consists almost entirely of white quartzite with an occasional bed of conglomerate. Owing to the persistent character of the formation and its difference in color from the associated rock, it is an excellent guide in working out the stratigraphy of the region, which is much complicated by numerous faults and folds.

The *Brasstown schist*, where not displaced by faulting, has a similar distribution to the Tusquitee quartzite, though it does not extend so far south as the latter. It is made up of banded slate and ottrelite schist having usually a dark, bluish color. Owing to its limited distribution it is only of minor stratigraphic importance.

The *Valleytown formation* consists of biotite schists, sericite schist, and mica gneiss, with a few beds of quartzite and conglomerate. In the Ellijay quadrangle south of Cherrylog it is described as a nearly homogeneous mass of sericite, mica schist, and siliceous slate, with some talcose material. The occurrence of graphitic schist beds are noted in the formation between Toccoa River and Ellijay. The formation is usually valley-forming, though north of Blue Ridge, extending to the state line, it forms a rather prominent ridge, as well as the narrow valleys on either side.

The *Murphy marble*, from an economic standpoint, is the most important of the metamorphic group of rocks in the state. It consists of holocrystalline limestone which in places becomes magnesian. The magnesian phase of the formation is commonly fine-grained, while the high-calcium phase is coarse-grained. It is usually white but in places is more or less banded or mottled with black owing to the presence of graphite. The formation enters the state from North Carolina in the vicinity of Culberson, from which point it continues southwest in one or more narrow belts, with a few interruptions due to faulting, to a point a few miles beyond Tate, Pickens County, the seat of Georgia's great marble industry. Marble very similar in texture and composition occurs many miles farther to the southwest in Haralson County, near Buchanan, which is supposed to be the southern extension of the Murphy marble. The formation is probably the equivalent of the Shady limestone, an unaltered magnesian limestone hereafter to be described.

The *Andrews schist* is a comparatively thin, unimportant calcareous schist overlying the Murphy marble near the Georgia-North Carolina line, and like the overlying Nottely quartzite is of very limited extent. It is made up almost entirely of dense quartzite which is highly resistant to weathering and is therefore ridge-forming.

UNALTERED CAMBRIAN

The Unaltered Cambrian rocks occupy the northwestern part of the state and are divided into the Lower, the Middle, and the Upper divisions, the first named being subdivided into the Weisner quartzite, Shady limestone, Cartersville formation, Apison shale, and Rome formation (Fig. 3).

The *Weisner quartzite*, which is the southern extension of a part of the Chilhowee sandstone of Tennessee, forms a prominent series of ridges and hills along the eastern margin of the Appalachian Valley as far south as Cartersville and a few miles beyond. At this point it is cut out by the Cartersville fault, but farther to the southwest it again appears in a small area near Esom Hill, where it forms the northern extension of a large area just across the state line in Alabama. The lithological character of the Weisner quartzite as described by Hayes is fine-grained and vitreous, though the formation also contains some beds of fine conglomerate and considerable siliceous shale. A few imperfectly preserved fossil remains, including brachiopods, corals, and worm tubes, all supposed to be Lower Cambrian, have been found in the formation in the vicinity of Cartersville and Emerson.

The *Shady limestone* lies immediately above the Weisner quartzite, and it has a like distribution. The formation consists chiefly of gray magnesian limestone usually massive but in places shaly and siliceous. It is of very great economic importance, as associated with its weathered product, occur more or less extensive deposits of barytes, iron ore, and manganese ore. Fossils are almost entirely absent, though in the vicinity of Cartersville a fossil sponge, a lower Cambrian form, has been found.

The *Cartersville formation*, as recently defined by Shearer, is known only in the Cartersville district. It is supposed to occupy the same position in the stratigraphic column as the Watauga shale of Tennessee and the Apison shales of Tennessee and Georgia. The formation has a limited distribution, being confined to one main belt less than twenty miles long. It consists mainly of highly aluminous shales, which are remarkable for their high potash contents, often as much as 10 per cent K_2O. Associated with the shales, which are chiefly of a gray or purplish color, there are often

COLUMNAR SECTION
PALEOZOIC ROCKS OF GEORGIA

ERA OR SYSTEM	PERIOD OR GROUP	FORMATION	COLUMNAR SECTION	THICKNESS IN FEET
CARBONIFEROUS	PENNSYLVANIAN	WALDEN SANDSTONE		930
		LOOKOUT FORMATION		500
	MISSISSIPPIAN	PENNINGTON SHALE		780 +
		BANGOR LIMESTONE (PROBABLY TIME EQUIVALENTS)		900
		FLOYD FORMATION (PROBABLY TIME EQUIVALENTS)		1,500 +
		FORT PAYNE CHERT		200
DEVONIAN	UPPER	CHATTANOOGA BLACK SHALE		20
	MIDDLE (ABSENT)			
	LOWER	FROG MOUNTAIN SANDSTONE AND ARMUCHEE CHERT		40
SILURIAN	UPPER (ABSENT)	ROCKWOOD FORMATION		1,600
	MIDDLE NIAGARAN			
	LOWER (ABSENT)			
ORDOVICIAN	UPPER	(WESTERN BASIN) CHICKAMAUGA FORMATION; (EASTERN BASIN) ROCKMART SLATE		2,500 +
	MIDDLE	CHICKAMAUGA LIMESTONE		200
	LOWER	KNOX DOLOMITE		5,000
CAMBRIAN	UPPER CAMBRIAN OR SARATOGAN			
	MIDDLE CAMBRIAN OR ACADIAN	CONASAUGA SHALE AND LIMESTONE		2,000
	LOWER CAMBRIAN OR GEORGIAN	ROME FORMATION		3,500
		APISON SHALE		1,000
		CARTERSVILLE FORMATION		1,000
		SHADY LIMESTONE		1,100 +
		WEISNER QUARTZITE		2,500 +

FIG. 3

found thin layers of feldspathic sandstone and quartzite, but these form only a minor part of the formation as a whole.

The *Apison shale* consists of varicolored argillaceous shales developed only in limited, elongated areas in Whitfield and Catoosa counties. Although the Apison is evidently approximately equivalent to the Cartersville formation in age, the exposures are in the western part of the valley.

The *Rome formation* consists of sandstone and shale and is confined to two belts near the center of the Appalachian Valley. The main belt, which is rarely more than two miles wide, extends from near Cave Spring, Floyd County, northeast through Rome to a point within about three miles northwest of Calhoun in Gordon County. The other belt commences near Villanow in Walker County and continues to the Georgia-Tennessee line a few miles northeast of Ringgold. A third belt which Hayes placed in this formation on the basis of stratigraphic position is above described as the Cartersville formation. Immediately overlying the Rome formation and apparently without any stratigraphic break are the only representatives of Upper Cambrian, namely the Conasauga formation and the lower division of the Knox dolomite formation.

The *Conasauga formation*, with the exception of the Knox dolomite, covers the largest surface area of any of the Cambrian series of Georgia. It is especially well developed along the eastern side of the Appalachian Valley, where it occurs in two main elongated but broad belts. The easternmost of these belts continues south from the Georgia-Tennessee line from Tennga to a point a few miles south of Cartersville, where it is cut off by the Cartersville fault, while the other belt, after being divided into minor belts and at points uniting with the easternmost belt, continues to the Alabama state line by way of Rome. Farther to the west are three narrow belts, one of which, lying to the west, traverses the entire northwestern corner of the state by way of Lafayette. The upper part of the formation is made up largely of olive-green and yellowish-green argillaceous shale, but the lower part consists mainly of grayish and bluish limestones locally oölitic and interstratified with the shale. The Conasauga formation contains an

abundant Cambrian fauna which has been studied by Professor C. D. Walcott.

The *Knox dolomite* is divided by an unconformity into a lower and upper division. The upper division on paleontological evidence has been referred to the Ordovician system and the lower to the Cambrian. The formation as a whole consists of a great thickness of magnesian limestones with much chert in places. It occurs in a large number of broad and narrow belts traversing the Appalachian Valley.

ORDOVICIAN SYSTEM

The *Chickamauga formation* represents both the Middle and the Upper group of the Ordovician system. It consists of sediments laid down in two separate basins. The rocks in the western part of the valley consist of interbedded limestones and shales outcropping in a number of long, narrow belts, while in the eastern part of the valley the formation is divided into the Chickamauga limestone and the Rockmart slate. The latter consists chiefly of dark-colored slates, with a few thin beds of sandstone and some limestone usually high in calcium.

SILURIAN SYSTEM

The *Rockwood formation,* which unconformably overlies the Chickamauga formation, is the only representative of the Silurian system. It consists of olive-green shales and thin-bedded sandstone, with one or more beds of fossiliferous iron ores. It occurs only in the western part of the Appalachian Valley, where it forms narrow belts at the base of the higher ridges and mountains capped with Carboniferous rock.

DEVONIAN SYSTEM

The *Chattanooga black shale* and the *Armuchee chert* are the only representatives of the Devonian system in Georgia. These two formations are separated from each other by an unconformity and are supposed to represent the Upper and Lower Devonian respectively, the middle part of the system being absent. The black shale, which attains a thickness of not more than twenty feet, is confined to the western part of the valley, where it occurs

in narrow outcrops with a linear distribution coextensive with the Rockwood formation. The Armuchee chert, which consists of bedded chert and thin beds of reddish-brown sandstone, is confined to a few small areas north of Rome.

CARBONIFEROUS SYSTEM

The *Fort Wayne chert* is the lowest member of the Mississippian group of the Carboniferous system and unconformably overlies the Chattanooga black shale. It consists essentially of siliceous limestone, with layers and nodules of chert made up in places largely of crinoid stems. The formation in the western part of the Appalachian Valley occupies narrow belts, while north of Rome it covers large, irregular areas.

The *Floyd shale* and the *Bangor limestone*, which also belong to the Mississippian group are probably stratigraphically equivalent, though one is largely shale and the other limestone. The former is best developed along the narrow valleys at the base of Lookout and Sand mountains, while the other occurs in numerous narrow belts in Floyd County and the adjacent counties both north and east of Rome.

The *Pennington shale* unconformably overlies the Bangor limestone and forms the uppermost series of the Mississippian group. It consists largely of shale, with sandstone in the upper portion. Its linear distribution is coextensive with the Bangor limestone.

The *Lookout formation* and the *Walden sandstone* are both members of the Pennsylvanian group. They are best developed in Lookout and Sand mountains, which constitute what is known as the Cumberland Plateau physiographic division of the state. They consist of sandstones, conglomerates, shales, and a number of commercial coal seams.

CRETACEOUS SYSTEM

The Cretaceous system, which rests unconformably on the old crystalline rocks, is confined to a narrow, irregular belt traversing the middle portion of the state in a southwest direction from Augusta to Columbus by Milledgeville and Macon. The total area covered by this system of rocks is approximately 250 square

miles. It is divided into an upper and a lower series, the latter being further divided into two formations, namely the Ripley and the Eutaw (Fig. 4).

The *Lower Cretaceous*, so far undifferentiated, lies immediately upon the crystalline rocks below and is unconformably overlain by the Eutaw. The basal unconformity represents an enormous time interval, including all Paleozoic time and the Triassic[1] and Jurassic periods of the Mesozoic time. The formation is made up predominantly of coarse-grained cross-bedded, arkosic sand, with a subordinate amount of white clays in the form of lenses. It forms an irregular belt varying from two to ten miles in width and extending entirely across the state.

The *Eutaw and Ripley formations*, each divided into two or more members, occupy an elongated area immediately south of the Lower Cretaceous between the Ocmulgee and Chattahoochee rivers. Both formations are of marine origin and consist mainly of calcareous, micaceous sand and dark-gray sandy clay, with some thin-bedded impure limestone. The upper member of the Ripley formation is unconformably overlain by the Midway formation, the basal member of the Eocene series.

TERTIARY SYSTEM

The Tertiary system of rocks has a far greater areal extent than any other system in the state. With the exception of a narrow belt of Quaternary along the Atlantic seaboard and narrow irregular belts of Cretaceous immediately south of the ancient Crystallines, it covers the entire Coastal Plain which comprises more than one-half the area of the state. The system is represented by the following series: the Eocene, the Oligocene, the Miocene, and the Pliocene. The first named is divided into five formations, the Midway, the Wilcox, the McBean, the Ocala, and the Keg Creek. The Keg Creek and the Ocala limestone formations both belong to the Jackson group, while the McBean formation belongs to Claiborne group.

[1] The Triassic rocks in Georgia are represented by diabase dikes which are widely distributed over the Piedmont Plateau.

COLUMNAR SECTION
COASTAL PLAIN OF GEORGIA

SYSTEM	SERIES	GROUP	FORMATION	MEMBER	COLUMNAR SECTION	THICKNESS FEET
QUATERNARY	RECENT					
			SATILLA			10-50
	PLEISTOCENE	COLUMBIA	OKEFENOKEE			5-40
			UNCONFORMITY			
			CHARLTON			?
TERTIARY	PLIOCENE (?)		DUPLIN MARL			10-15
	MIOCENE		MARKS HEAD MARL			45
			UNCONFORMITY			
	OLIGOCENE	APALACHICOLA	ALUM BLUFF			150
			CHATTAHOOCHEE			150
			UNCONFORMITY			
			VICKSBURG			100
	EOCENE	JACKSON	KEG CREEK SAND	TWIGGS CLAY		200-300
			OCALA LIMESTONE			
		CLAIBORNE	McBEAN			100
			UNCONFORMITY			
			WILCOX			150
			UNCONFORMITY			
			MIDWAY			400
			UNCONFORMITY			
CRETACEOUS	UPPER		RIPLEY	PROVIDENCE SAND		950
				MARINE BEDS		
				CUSSETA SAND		
			EUTAW	TOMBIGBEE SAND		560
				MARINE BEDS		
			UNCONFORMITY			
	LOWER		UNDIFFERENTIATED			350-600
			UNCONFORMITY			
ARCHEAN						

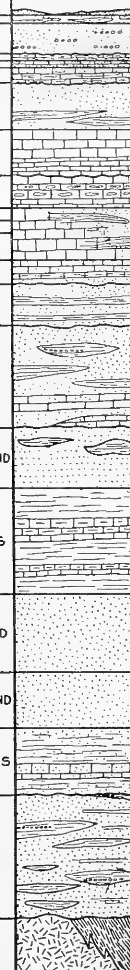

FIG. 4

EOCENE SERIES

The *Midway formation*, which forms the base of the Eocene series, lies unconformably upon the upper member of the Cretaceous and is unconformably overlain by the Wilcox. It consists of sand, clay, and marl, and forms a narrow northeast-southwest belt extending from Fort Gaines on Chattahoochee River to a point a short distance east of Flint River in Houston County. At no place does it exceed twelve miles in width.

The *Wilcox formation* has a distribution similar to the Midway, though it probably does not extend beyond Flint River. It is made up mainly of sandy, glauconitic shell marl and laminated, sandy, dark-colored lignitic clay. Near Flint River pure beds of white clay occur, with red and varicolored sand.

The *McBean formation* forms an extremely irregular belt which varies from two to thirty miles or more in width and extends entirely across the state. East of Ocmulgee River it rests unconformably on the strata of Lower Cretaceous age, while between Flint and Chattahoochee rivers it rests unconformably upon the Wilcox formation. It consists of shell marl, sandy limestone, glauconitic, calcareous sands, and clays in the form of fuller's earth.

The *Ocala limestone*, which is best developed between Ocmulgee and Chattahoochee rivers, is the main representative of the Jackson group in Georgia. Its eastern boundary lies usually a few miles west of Flint River, whence it extends south and west as a broad belt to the Georgia-Alabama-Florida state line, with an average width of more than thirty-five miles. The formation, as the name suggests, is made up of limestone with more or less chert in places.

OLIGOCENE SERIES

The *Oligocene series* is represented by the Vicksburg, the Chattahoochee, and the Alum Bluff formations, subdivisions of the Appalachicola group. The three formations are confined largely to the southern part of the Coastal Plain near the Georgia-Florida state line and to irregular areas southeast and southwest of Macon. The Vicksburg and the Chattahoochee formations, which are separated by an unconformity, consist largely of limestone, while the Alum Bluff formation is made up mainly of sands and clays.

MIOCENE SERIES

The *Marks Head Marl* and the *Duplin marl* are the only formations belonging to the Miocene series. These two formations, which are best developed at Porters Landing on Savannah River, consist mainly of marls, sands, and clays. The Marks Head marl unconformably overlies the Alum Bluff formation.

PLIOCENE SERIES

The *Charlton formation*, which is supposed to belong to the Pliocene series, occurs along St. Marys and Satilla rivers in the extreme southern part of the state. The formation consists mainly of shell marls.

The *Altamaha* (*Lafayette?*) *formation*, not shown in the columnar section, has the greatest areal extent of any formation in the Coastal Plain, covering approximately 21,000 square miles. Like the underlying Charlton formation, it is supposed to be Pliocene. The formation has a maximum thickness of less than three hundred feet and consists chiefly of sand, gravel, and clay, which in places become indurated. With the exception of a few fragments of wood it is entirely free from organic remains.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

The Pleistocene is represented by the Okefenokee and the Satilla formations, divisions of the Columbia group. These formations form a belt along the Atlantic Coast, with a width from twenty to fifty miles. The Okefenokee consists chiefly of gray sand, and the Satilla is made up of greenish and bluish marine clays and gray and yellow sands.

SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE PRE-CAMBRIAN OF NORTHERN QUEBEC

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PART II

DETAILED AREAL DESCRIPTIONS

In the following descriptions the structures of the separate areas studied will be briefly stated, with the conclusions as to succession which were made in each area. Fig. 3 shows the relative positions of the areas described. In the Opawika, Father's Lake, Windy Lake, and Eau Jaune–Obatogamau areas, where the rocks are largely of the basal lava series, or Abitibi volcanics, the determinations of the structure were in each case the result of a large number of observations, using the methods described, on the attitude of the lava flows over as wide an area as the nature of the work permitted. The results of each determination by any one of the methods described were checked whenever possible by the application of one or more of the other criteria as well. No other stratigraphic methods were applied or, in fact, were applicable. For the sake of brevity, therefore, the methods of determination of the structure in the separate instances will not be stated, as this would only involve unnecessary repetition.

The Opawika area.—The Opawika area (Fig.4) borders the Opawika River near its junction with the Waswanipi River. It includes the northern portion of Tush Lake, Opawika Lake, and the Opawika River from Opawika Lake down to Sturgeon fall. The rocks are a series of closely folded lavas and tuffs and are unusually well exposed. The axes of the folds strike N. 75° E., but their plunge was not determined. The approximate position of these axes is shown on the map. The southernmost fold, on Tush Lake, is an anticline, the southern limb of which is cut off by granite. The axis of the syncline to the north follows approximately the

south shore of Opawika Lake. The west end of the lake breaks across into the next anticline to the north.

The rocks in the southern anticline are andesites, fairly massive and without pillow structures. Dips vary from 65° to 90°. On the north side of this anticline, in the long east bay of Tush Lake, coarse

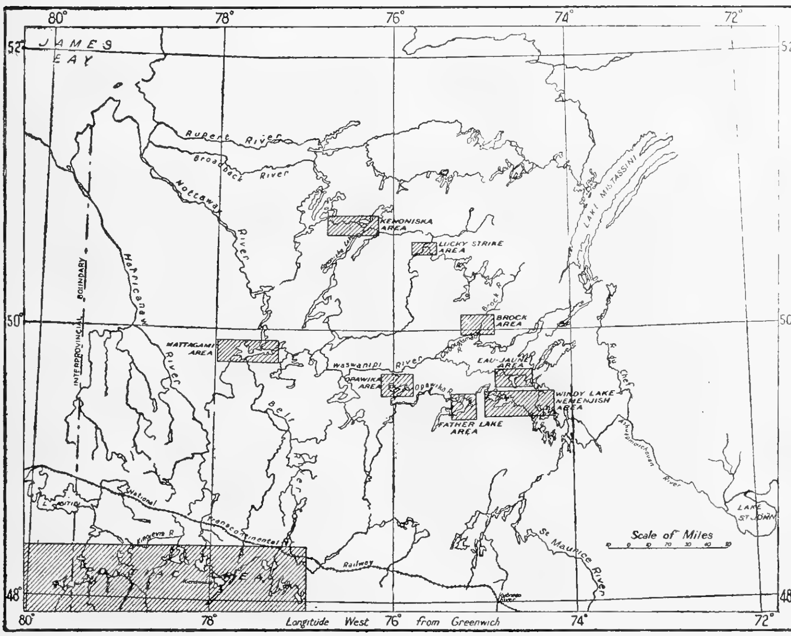

FIG. 3.—Key map of the part of northern Quebec dealt with in this paper, and the positions of the small areas particularly described.

andesitic tuffs lie conformably on the andesites. They are not bedded.

Along the axis of the syncline, on the south shore of the western end of Opawika Lake, a flow of highly acid quartz porphyry, a translucent, greenish-white rock, conformably overlies the andesite. In the anticline to the north, lavas of acidity intermediate between the quartz porphyry and the andesite outcrop until the normal andesite is again reached. The latter continues to outcrop as far as Sturgeon fall.

The succession in this area is:

Rhyolite porphyry lavas
Intermediate lavas
Andesites and andesite tuffs at or near the top of the flows

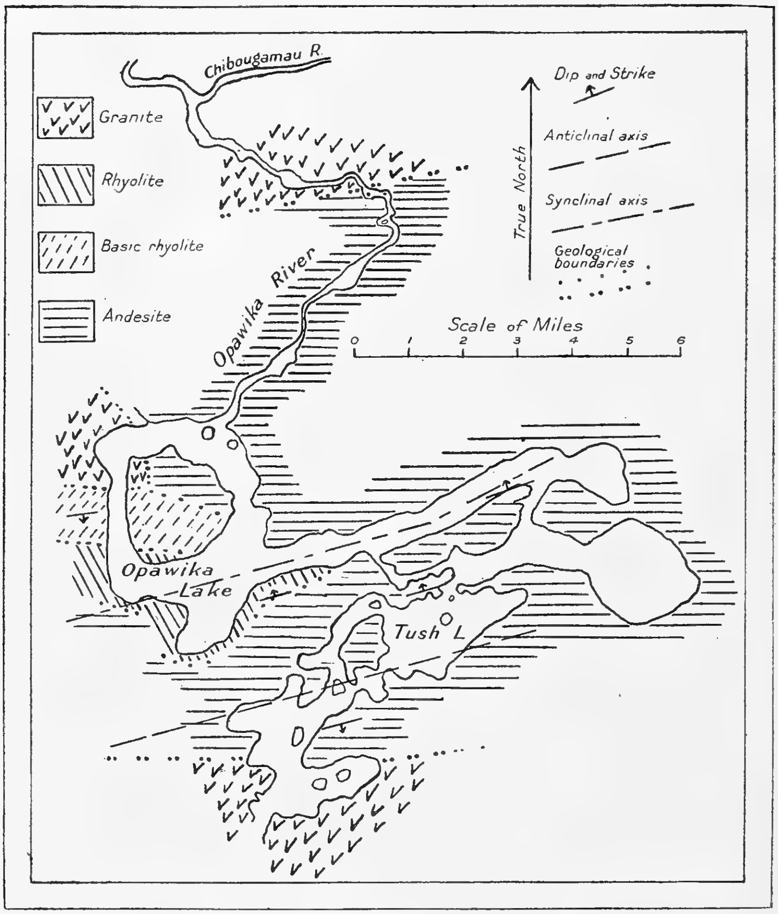

FIG. 4.—The Opawika area

It seems possible that the structure of this whole belt is that of a synclinorium, as the uppermost beds are found only near the the median line of the belt. However, this distribution may equally well be due to irregularity of original deposition, more especially as

the rhyolite lava was probably viscous and did not spread out far from its vent.

Father's Lake area.—The structure of this small area appears to be that of a synclinal drag fold, although the lack of outcrops on the northwest side of the lake makes its complete determination uncertain (Fig. 5). The flows around the southern border of the area

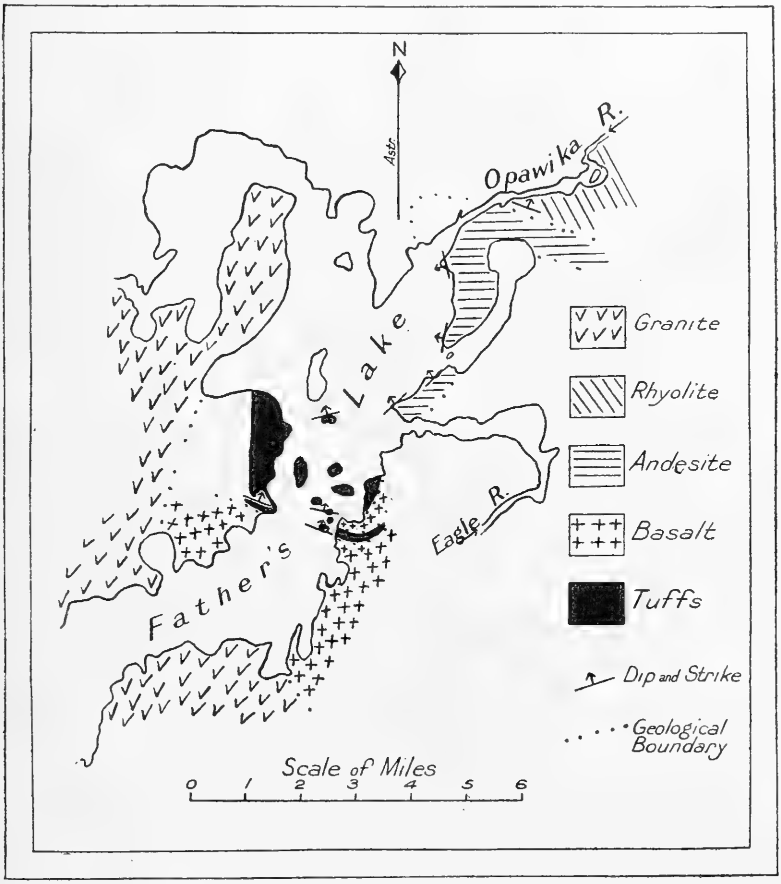

FIG. 5.—The Father's Lake area

are basaltic in composition and quite thin, some of them less than ten feet in thickness. Above them lie one or two flows of porphyritic basalt, characterized by feldspar phenocrysts up to one-half

inch in diameter. Beds of basic sediments overlie conformably the porphyritic basalts and in one place are interbedded with them. The beds approximate one inch in thickness, and the thickness remains uniform over the outcrops, which in some cases were exposed two hundred feet or more along the strike. The sediments are of tuffaceous composition and vary from grayish or reddish cherty rock, which may be in part a deposit from silica-bearing solutions accompanying the lava flows, to black hornblendic material, probably recrystallized volcanic dust. In places they are filled with lenses of gabbroid material averaging about four inches in length by one-quarter inch in width.

North of the mouth of the east bay into which the Eagle River empties, outcrops of andesite occur, with a northeast strike and a dip to the northwest. The strike swings gradually to the north, then to the east at the mouth of the Opawika River, where they are overlain by rhyolite. It is doubtful what relation the andesites bear to the basalts and sediments. The mapping as it stands leads to the inference that faulting of some magnitude has taken place along the east bay into which Eagle River empties, but it is impossible to prove this, as the rocks here are all heavily drift covered. The map, however, is a rather inferior grade of track survey, and the impression gained in the field by assuming a projection along the strike was that the andesites overlie the basalts and part of the sediments and underlie the remainder of the sediments.

It may be observed that the basaltic flows in this area have no ellipsoidal textures, while the andesites are ellipsoidal. The significance of the fact will be discussed in a subsequent section. The succession in the Father's Lake area is

Rhyolite	Tuffaceous sediments
Andesite	Porphyritic basalts
	Basalts

Windy Lake–Nemenjish area.—The structure of the Windy Lake–Nemenjish (Fig. 6) area is monoclinal, so far as known, with a general east-west strike and a southward dip. This structure has been attained by strike faulting, with consequent repetition of outcrops. One large fault, whose south side was upthrown, was observed on Windy Lake, and possibly others occur to the south

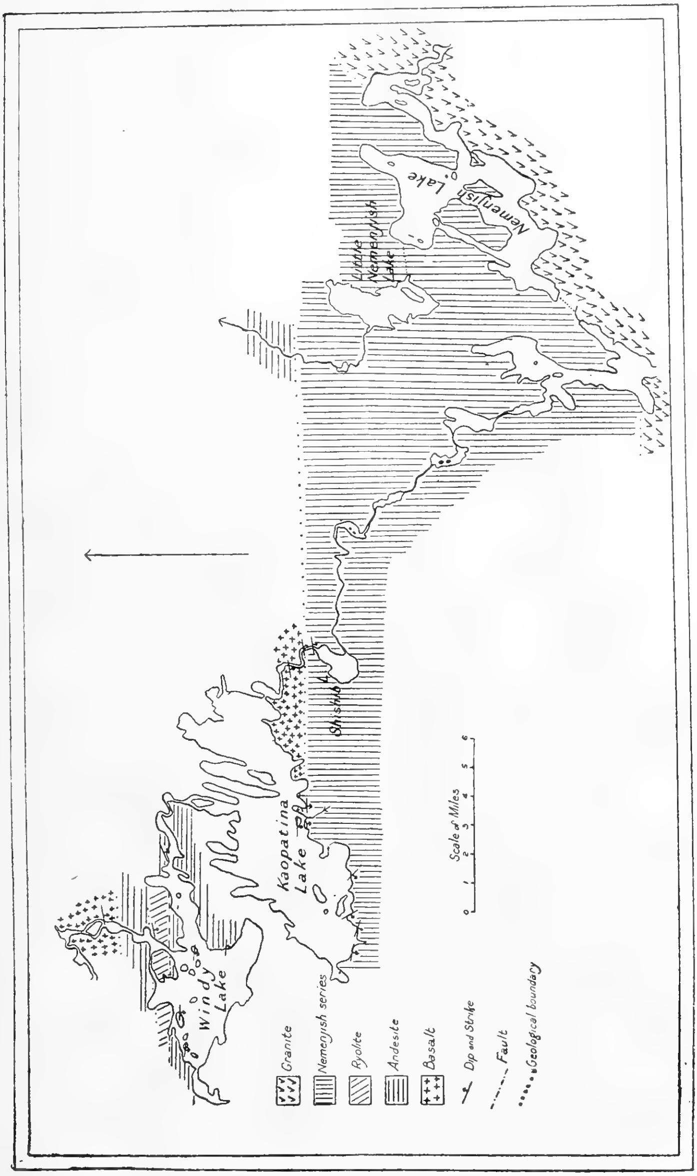

FIG. 6.—The Windy Lake–Nemenjish area

on Kaopatina Lake where most of the outcrops are hidden by a heavy cover of drift. The plunge of the folding appears to have been to the east, for near the west end of the area the strikes assume more of a north-south trend, which may indicate the presence of the axis of a cross-fold near-by, though it may be due merely to the subsequent disturbing influence of the granite intrusion to the west.

The basal rocks of the series, found on the river above Bras Coupe Lake, are very basic basalts, one flow of which is unusually fresh and glassy. These, like the basal flows on Father's Lake, possess no ellipsoidal structures. They are overlain to the south, as far as the outlet of Windy Lake, by andesites characterized by good pillow structures. A thin body of somewhat more acid lava lies above the andesites, and on this is found a bed of coarsely fragmental rhyolite, approximately 2,000 feet thick. Its composition is identical with that of the massive rhyolite porphyry on Opawika Lake. This fragmental rock shows no trace of bedding, as would a water-laid sediment, although we may conclude from the evidence of the pillow structure in the underlying andesites that the sea or a lake existed here at the time. It seems necessary to conclude therefore that the rock was not ejected as a tuff, but as a lava, and that its present fragmental condition is due to subaqueous extrusion, and hence corresponds to the pillow structure in the more basic lavas. Corroborative of this conclusion, rhyolite porphyry in the same fragmental condition was also found on Obatogamau Lake, where it rests directly on well-bedded tuffs, thus again indicating its subaqueous extrusion.

The southern boundary of the fragmental rhyolite is a fault, to the south of which the ellipsoidal andesites again outcrop.

Between the south shore of Windy Lake and the south shore of Kaopatina Lake the structure is unknown, as outcrops are not numerous or large enough for its determination, although there are sufficient to indicate that the formation is continuous across the gap. However, since the outcrops on the south side of Kaopatina Lake are of the basalts of the series, which elsewhere always occupy a basal position, and since they still maintain an east-west strike and a dip to the south, the intervening drift-covered gap must be supposed to be underlain by the south limb of a syncline whose

north limb is found on Windy Lake, and by the crest of the next anticline; or else it must be assumed that another strike fault again upthrows the lower beds on the south.

The determination of the attitude of the beds on the south side of Kaopatina Lake, the correctness of which is a matter of great importance, was made with the greatest care in three different places, in each case by tracing a flow from its coarse-grained base up to its fine-grained top, where it was found in contact with the coarse-grained base of another flow. Lying above these basalts, and conformable on them, is a thick series of thin-bedded tuffs, interbedded with which, and rather high up in the series, is a thin flow of rhyolite porphyry. This flow is of small areal extent and appears only in the west end of the lake.

On the Opawika River above Kaopatina Lake the same relations were observed. Rather thick flows of basalt with a strike of N. 80° E. and a dip of 80° south are here conformably overlain by thin-bedded, rather basic tuffs. The plane of contact is occupied by a dyke of granite, which appears to be an offshoot of a larger mass to the east, as the dyke was not observed along the contact farther to the west, and where observed widens rapidly toward the east. The strike and dip of the tuffs is identical with that of the underlying basalt. About thirty feet above the contact a basalt flow about four feet in thickness is interbedded with the tuffs.

Passing higher into the tuffs toward the south, it was observed that the beds of tuff begin to be mingled with beds of metamorphosed clastic sediment. The latter become more numerous and finally replace the tuffaceous beds completely. At the same time the thickness of the separate beds increases until on the south side of Lake Shishib the beds are so heavy and massive that a bedding plane can rarely be observed.

The thick-bedded rocks on Lake Shishib are garnetiferous mica gneisses, probably recrystallized impure sandstones, or sandy shales. They continue to outcrop at intervals up the Opawika River to Dinachagama Lake, where they begin to be intruded by granite masses. They were traced across the Height of Land into Lake Nemenjish, on the north shore of which the sediments are well exposed and comparatively undisturbed by granite intrusion. Here

the mica gneiss is interbedded with garnetiferous mica gneiss, hornblende gneiss, or amphibolite, garnetiferous hornblende gneiss, and crystalline limestone. The garnetiferous mica gneiss is identical in composition with the non-garnetiferous type, except for the presence of the garnets. The hornblende gneiss, or amphibolite, is a black, gabbroid rock, which may be of igneous origin, although no evidence of such origin could be obtained, and it is interbedded with the other rocks with perfect conformity. The garnetiferous hornblende gneiss is very similar to the non-garnetiferous type, with the addition of garnets; as in the case of the other, no evidence of an igneous origin could be obtained for it, and it is suspected that it may be a recrystallized, impure, calcareous sediment. In support of this view is the fact that the only crystalline limestone found, consisting of two beds, each about a foot in thickness, is interbedded with the garnetiferous hornblende gneisses.

This series of sediments has been named by the writer the Nemenjish series, from the lake on which it is best exposed.

The succession in these areas is therefore as follows:

Windy Lake Area	Kaopatina-Nemenjish Area
Tuffaceous sediments	Nemenjish series: Interbedded garnetiferous and non-garnetiferous mica gneisses and hornblende gneisses, with crystalline limestones
Rhyolite porphyry	Garnetiferous mica gneisses
Flows of intermediate composition	Interbedded mica gneisses and basic tuffaceous sediments
Andesites	
Basalts	Basalts

Eau Jaune–Obatogamau area.—This area includes Eau Jaune Lake and part of Obatogamau Lake (Fig. 7), together with a part of Presqu'ile Lake; but outcrops below Eau Jaune Lake are so scarce that the structure of this latter portion of the area could not be determined. The area is of interest mainly because of its conspicuous cross-folding. In the other areas described the axes of folding have a general east-west strike, and the cross-folding has been sufficient only to give these axes plunges varying from 15° to 30°. In the Eau Jaune area and, it may also be remarked, in the sediments on Nemenjish Lake, the cross-folding is as intense

or more so than the folding along east-west axes. As these are the most easterly areas studied, it is not known whether the cross-folding represents merely a local crumpling along some plane of weakness or whether the areas are on the western edge of a region folded along northeast and southwest axes. A study of the reports and maps of the country to the east and north, however, makes the latter supposition seem probable.

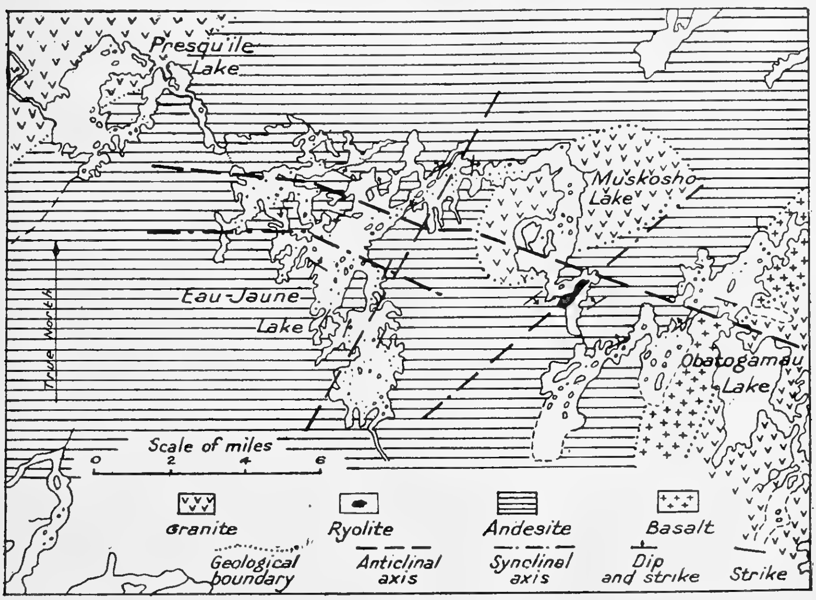

FIG. 7.—The Eau Jaune–Obatogamau area

The position and direction of the axes of folding are shown on the map. The one set, corresponding with those in the other areas described, strikes S. 70° E., apparently swinging in the western part of the area to east. The other set strikes N. 35° E. on Eau Jaune Lake, and N. 50° E. on Obatogamau Lake. The succession and distribution of beds suggest that the larger structure is that of a synclinorium whose axis has a northeasterly strike. The rocks on the eastern side of the area are basalts. Andesites overlie the basalts on the eastern side and outcrop also in the western part. Their composition gradually becomes more acid toward the center,

and along the central synclinal axis there lies a small area of basic tuffs, overlain by twenty to thirty feet of fragmental rhyolite porphyry. The succession was well determined, and the distribution would indicate conclusively a general synclinal structure were it not suspected, as in the Opawika area, that the rhyolites are localized in their original distribution.

The best determinations of structure were made on the western part of Obatogamau Lake and the eastern part of Eau Jaune Lake, where the presence of large and easily determinable ellipsoidal structures rendered work easy. Time did not permit of the intensive work necessary for the determination of the structures of the basalts in the northern and eastern parts of Obatogamau Lake, while outcrops are rare along the eastern shores of Eau Jaune Lake.

The basalts of Obatogamau Lake are characterized by ellipsoidal structures, in contrast with the basalts of the areas to the west. The ellipsoidal structures in the basalts are small and difficult of recognition, except on unusually clean surfaces, so that they do not aid greatly in the determination of the attitudes of the flows. If this structure is an indication of submarine extrusion, however, their occurrence at this point will indicate that the seashore at the time of the basaltic extrusion lay between Obatogamau and Kaopatina lakes. From this point it must have transgressed rapidly westward as extrusion proceeded.

The succession as determined in this area is:

Rhyolite porphyry, fragmental	Andesite flows
Andesite tuffs	Basalt flows

Brock area.—The Brock area (Fig. 8) is situated at the confluence of the Brock and Chibougamau rivers. Unfortunately outcrops are poor in this locality on account of the cover of stratified sands extending up the Chibougamau valley.

The basal rocks are a series of basic lavas which are here more schistose than those farther to the south, presumably because of the shear between them and the overlying formation at the time of folding. Their structure was not determined. To the north of these is a series of sediments, which were found to form the south limb of a syncline, the north limb of which has been cut off by granite. At the southern contact of the series lies a heavy band

of conglomerate. Only one outcrop of this was seen, about a mile below the mouth of the Brock River. At this point the conglomerate is very schistose. The pebbles are so numerous as almost to exclude matrix, which is a rather impure sand. About 30 per cent of the pebbles are hornblende granite; the remainder are various basic rocks, now so sheared that their original composition is indeterminable, although it is clear that they are of several kinds. The stresses to which the rock has been subjected have deformed the pebbles according to their original hardness. The softer have been

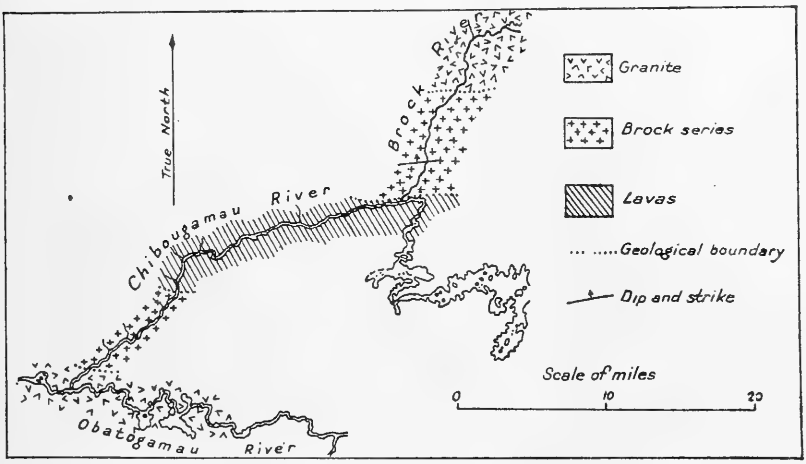

FIG. 8.—The Brock area

converted into narrow strings several inches in length by a fraction of an inch in width; harder ones have been flattened into lenses the shape of which depends on the original hardness; while those of granite, the most resistant, have been deformed by fracture rather than by flow, and still retain much of their original shape. The softer pebbles have flowed around the harder, accommodating themselves most closely to all their curves. Fig. 9 illustrates this conglomerate. The almost undeformed granite pebbles are well shown; in some cases even the fractures in them, inclined at about 45° to the planes of schistosity, may be seen. Some of the more prominent pebbles of softer materials are also clearly visible, with the manner in which they have flowed around the harder granites.

The rocks directly overlying the conglomerate are drift-hidden, but the next outcrops to the north are of mica gneiss and hornblende gneiss, which probably represent the recrystallized product of sandy shales. To the north of this, beds of altered impure sandstone and grit are found, beyond which mica and hornblende gneisses again appear. The latter rocks continue to outcrop to the northern limit of the area, where they are intruded and cut off by granite.

FIG. 9.—Conglomerate about a mile below the mouth of the Brock River

The rocks of the area were determined from observations on a number of drag folds, to form the south limb of a syncline or the north limb of an anticline. The axial planes of secondary drag folds were observed to dip toward the north. Hence the folding is of the abnormal type. The axes of these drag folds plunge, where observed on the Brock River, about 22° to the west. Hence the plunge of the primary fold at this point is to the west. The general strike of the axes of these drag folds is N. 80° to 85° E.

About twenty-five miles down the Chibougamau River, near the mouth of the Opawika, another wide area of rocks similar to the upper beds of this series of sediments outcrops. The basal conglomerate, however, was not found here, so that it is possible that

these beds may not belong to this series, but may be fine-grained sediments of the Nemenjish series. The beds dip toward the north, but a consideration of the relative movement of the beds inferred from the shape of the drag folds showed that they form the south limb of an overturned anticline. It seems possible therefore that these beds are the south limb of the anticline of which the Brock sediments form the north limb. If so, the axial plane of this large fold dips to the north.

The succession in the Brock area therefore in order of age appears to be:

Mica and hornblende schists
Grits
Conglomerate
  Uncomformity
Green schists and basalts

Lucky Strike area.—The Lucky Strike area (Fig. 10) lies at and above the junction of Lucky Strike creek with the south branch of the Broadback River. Here, as in the Brock area, the youngest rocks are granites, which intrude a series of sediments, consisting of conglomerate at the base, passing upward into arkose or greywacke, and then into muscovite schists which probably represent impure sandstone. Beds which may have overlain these have been cut off by the granite. All the beds are much deformed, although not so much as in the Brock area. The following pebbles were observed in the conglomerate: hornblende granite, quartz biotite schist, anorthosite (one only), hornblende schist, made up almost wholly of hornblende needles; hornblende schist containing 30 to 40 per cent plagioclase, quartz porphyry, bedded chert, and others which were originally of softer rock and are now so deformed as to render their original nature indeterminable. Many of these pebbles are recognizable as having been derived from the lava series, so that the conglomerate is evidently unconformable above it. The harder pebbles have suffered little or no deformation and are well rounded, indicating long attrition before deposition in their present position.

The older series is not well exposed in this locality. Directly underlying the conglomerate in one place is found a garnetiferous

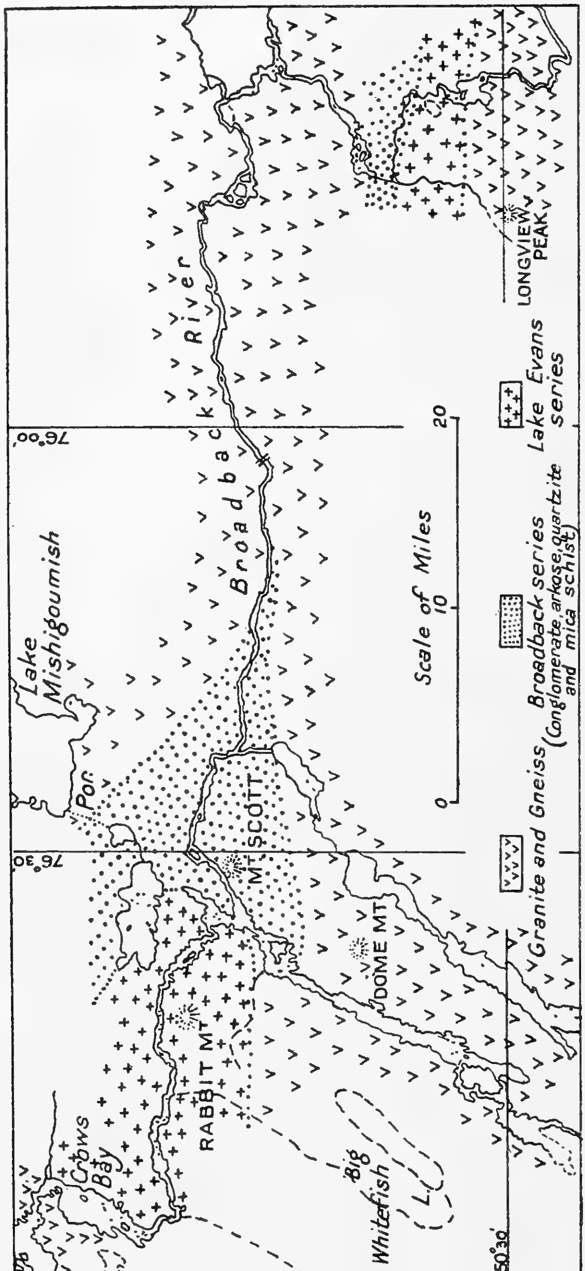

FIG. 10.—The Kenoniska area (about Mount Scott) and Lucky Strike area (north of Longview peak)

mica gneiss, identical in composition with the corresponding garnetiferous gneiss of the Nemenjish series on the Opawika River. Below this, in scattered outcrops, were observed basalts, basic intrusives, tuffs, and carbonate schists.

The succession in this area is therefore:

Broadback series, sandstone, now muscovite schist, arkose or greywacke, conglomerate
Unconformity
Nemenjish series, garnetiferous mica gneiss
Basic intrusives, basalts, tuffs, carbonate schists

Kenoniska area.—This area (Fig. 10) lies at the north end of Kenoniska Lake, on the Broadback River. It was mapped in part during the work of 1912. The map published at that time included the results of information gained by an earlier observer, which re-examination by the writer in 1914 proved to have been incorrect. As a result the formation boundaries shown on the map of 1912 are not to be accepted as final.

The geologic section in this area is very similar to that found in the Lucky Strike area, but is of more value, partly because the section is better exposed and more complete, and partly because undeformed rocks are to be found. The structure of the area is that of an anticline about ten miles in width, both limbs of which are cut off by granite. The anticline plunges to the east. The rocks on the limbs are very much sheared, but at the crest of the anticline, which is seen about five miles above Kenoniska Lake, the shearing has been so slight that even the slightest foliation can barely be detected.

The uppermost series, which was termed the Broadback series by the writer in 1912, consists of sediments which lie unconformably on an older series consisting mainly of lavas. At the base of the sedimentary series there are two heavy bands of conglomerate, separated by a thick band of fine-grained greywacke containing occasional pebbles. Above the conglomerate occur in order arkose, a thin band of quartzite, and mica schist. The latter includes both muscovite and biotite schists, of which the biotite schists are the larger in amount. The muscovite schists are probably the metamorphosed equivalent of very siliceous shales, the biotite schists of less siliceous shales.

The conglomerate on the limbs of the fold has been so sheared as to deform all the pebbles, as in the case of the conglomerate described in the Brock area. At the nose of the anticline, however, the rock is undeformed. The number of pebbles is so great that very little of the greywacke matrix is observable. The majority are unusually well rounded and of all sizes, up to eight inches in diameter. The material is very poorly assorted and markedly cross-bedded. The variety of the pebbles is great. About 50 per cent of the total number are of light-colored biotite granite; a few, about 4 or 5 per cent, of a still more siliceous granite, with almost no ferromagnesian mineral; 10 to 15 per cent consist of dark, bluish chert, often banded; while the remaining 30 per cent are quartz and various basic rocks, hornblende schist, andesite, etc., most of which can be matched in the lavas below.

The underlying series, which was named the Lake Evans series in 1912 consists near the base of basalts overlain by porphyritic andesites. Some thin-bedded, fine-grained, slaty tuffs were found overlying the andesites on Storm Lake; probably overlying these tuffs, and directly underlying the Broadback conglomerate, are some thin beds of garnetiferous mica gneiss, petrographically similar to certain of the members of the Nemenjish series. The structure of these rocks could not be worked out in detail on account of lack of outcrops, but the strike and dip of the bedding, wherever observable, is approximately parallel to the bedding of the overlying Broadback sediments.

As already stated, the general structure of this area is that of an anticline, whose axis has a strike of S. 75° E., and a low plunge to the east. If the axis of this fold be projected eastward across the intervening granite area, it is found to pass through the Lucky Strike area; so that these two areas probably form the two limbs of a large synclinal cross-fold, whose axis strikes N. 15° E. If so, the plunge of the Lucky Strike anticline, which was not determined in the field, must be toward the west.

The succession in the Kenoniska area therefore is:

Mica schist	Nemenjish series (?) garnetiferous mica schist
Quartzite	Slaty tuffs
Arkose	Andesites
Conglomerate	Basalts
Unconformity	

Mattagami area.—This area (Fig. 11), which lies on Mattagami Lake, has been briefly examined by the writer, but has been studied in detail by J. A. Bancroft.[1] The following is a summarized description of the more important points of composition and structure described by him.

The rocks include, as in the three foregoing areas, an overlying sedimentary and an older lava series. The sediments have been named by Bancroft the Mattagami series. They form a belt underlying the bed of the lake which outcrops at intervals along its shores over a distance of about fifteen miles. They consist almost wholly

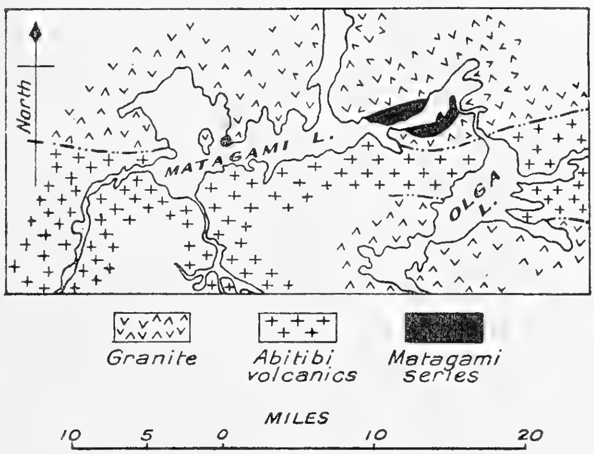

FIG. 11.—The Mattagami area

of quartz biotite schists, which are probably the metamorphosed equivalent of impure sandstones; these pass into conglomerate in places by the addition of pebbles of all sizes up to six inches in diameter. The pebbles are always scattered, never crowded together as in the conglomerates already described. However, it may be that if the series were better exposed bands of the more characteristic conglomerate would be seen. The deformation has been so great that all the pebbles with the exception of the hard granites have been squeezed, flattened, and in many cases reduced to narrow strings; while even the granites have been much granulated and recrystallized. On this account the recognition of the

[1] *Report on Mining Operations*, Quebec, Department of Colonization, Mines, and Fisheries, 1912, p. 131.

original nature of the pebbles is difficult. About 60 to 70 per cent of them are of granite; the remainder includes diorite, aplites, and biotite and hornblende schists.

Bancroft considers these sediments as probably unconformable on the series of lavas that lies to the south. The structure is difficult to determine, as the granite intrusions have cut off the sediments to the north, and have stoped their way to the lavas. Bancroft is of the opinion that the structure is that of a tight syncline; however, it appears equally probable that the present band represents only the south limb of a syncline, whose north limb has been cut off by granite. The writer inclines to the belief that the structure of the whole belt between Mattagami Lake and the National Transcontinental Railway is a great anticlinorium, the Mattagami series of sediments representing the north limb, the sediments of the Pontiac series the south limb. This theory, however, is unsupported by facts other than the petrographic resemblance of the sediments of these two groups and a general parallelism in their strike. It can probably never be proved by field evidence, as outcrops over the intervening territory are too small and scattered to make any continuous determination of structure.

To the south of the Mattagami series lie the supposedly older rocks, consisting of lavas, intrusives, and tuffs. The lavas include andesites and basalts principally, some of them distinguished by beautiful ellipsoidal structures. Slaty tuffs were observed in a few places. The strike of these rocks, where observed, is in general east-west, like that of the overlying sediments. The most important intrusive in the vicinity of Mattagami Lake is a large body of very coarse, feldspathic gabbro, petrographically identical with the gabbros which in other localities have been observed to grade into anorthosites, and probably to be correlated with them. It intrudes the lava series, but does not ascend as high as the contact with the sedimentary series; hence its relation to the sedimentary series is indefinite.

The succession in the Mattagami area therefore appears to be:

Mica schists
Conglomerate
Uncomformity
Basic intrusives
Basalts, andesites, rhyolites, and tuffs

Pontiac area.—The Pontiac area (Fig. 12) lies far to the south of the Brock, Broadback, and Mattagami areas but its rocks are strikingly similar. It is found to the south of the National Transcontinental Railway with its western end close to the Ontario-Quebec boundary; it is nearly one hundred miles in length by twelve in breadth. The rocks have been studied by M. E. Wilson[1] and J. A. Bancroft.[2] The following is a summarized account of their descriptions.

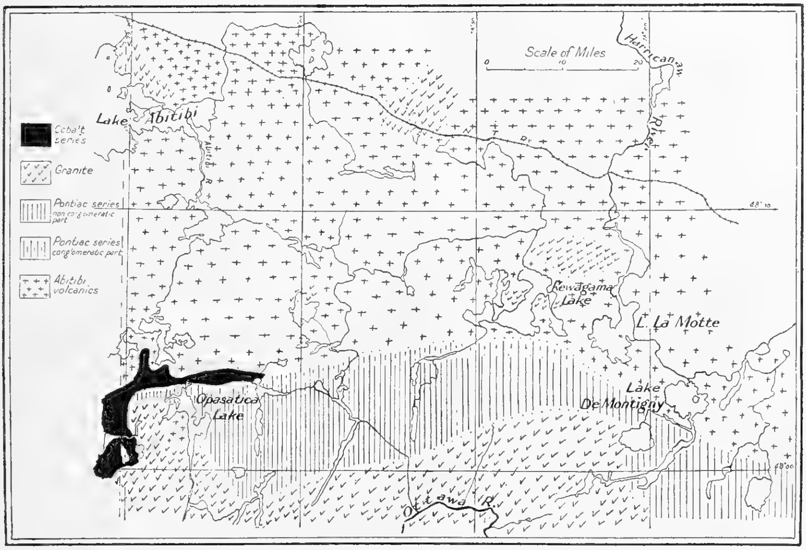

FIG. 12.—The Pontiac area

The rocks of the region fall into two general classes, a volcanic complex and a series of metamorphosed clastic sediments, termed by Wilson the Pontiac series. The Pontiac series is cut off on the south by intrusions of granite; the volcanic complex lies to the north of it. The band of sediments averages ten miles in width; the major part of this, about nine miles, is underlain by mica schist, with which is associated some hornblende schist and amphibolite.

[1] *Geol. Surv. Can.*, Mem. No. 39, 1914.

[2] *Report on Mining Operations for 1911*, Department of Colonization, Mines, and Fisheries, Quebec, p. 160; 1912, p. 199.

Toward the northern edge mashed arkose, greywacke, and conglomerate are found. The mica schist is a fine-grained rock consisting essentially of quartz and biotite usually with some feldspar. The arkose and greywacke are of much the same composition, though coarser in grain; they differ from each other only in the relative proportions of acid and basic fragments they contain. Both pass into conglomerate by the gradual addition of pebbles.

The composition of the conglomerate apparently varies a great deal from place to place. Wilson states that in the more western portions of the area studied by him he found pebbles only of granite, rhyolite, and quartz porphyry and none of the more basic rocks. Bancroft, on the contrary, working in the more eastern parts of the area, reports the majority of the pebbles to be of greenstone, although pebbles of granite and diorite are not uncommon. Metamorphism has squeezed and flattened all the pebbles more or less, converting the softer of them often into mere strings.

The Pontiac series overlies the volcanic complex unconformably according to Bancroft, as most of the pebbles of the conglomerate can be matched in the rocks below. Wilson, who did not find outcrops containing the more basic pebbles, doubts the uncomformity and is inclined to believe that the sedimentary series is older than the volcanic, since the general dip is steeply to the north. To secure further evidence, if possible, on this question in dispute, the writer visited Lake de Montigny in 1917 to examine the contact there. The contact itself has been exposed here in workings of some prospectors, and the lavas to the north are well exposed. The examination by the methods outlined in the beginning of this paper indicated that the south side of the flows is the uppermost. This evidence therefore confirms Bancroft's conclusion that the sediments overlie the flows, and some further support to it is given by the similarity of the Pontiac series to the Brock and Broadback series, both of which are undoubtedly younger than the volcanics. The northward dip must be ascribed to overturned folding.

The general trend of the strike of these rocks is east-west, and the dip, as stated, steeply north. Bancroft is inclined to believe that they form a tight syncline, but against this hypothesis lies the

fact that the conglomerate member is found only on the north side of the band of sediments. It seems more probable that they form the north limb of a syncline, whose south limb has been stoped off by the granite, while its anticlinal continuation to the north has been removed by erosion. If this is the case, the axial plane of this syncline must dip to the north.

Both Wilson and Bancroft have described all the sediments as parts of one sedimentary series. Since their work was published, however, several facts have come to light which are difficult of explanation if the rocks are to be considered as a single series, while the fact that outcrops are exceedingly poor in this district, owing to the heavy cover of glacial lake clays, renders it possible that two or more series of metamorphosed sediments have been inadvertently grouped together. The facts which tend to throw doubt on their interpretations are:

1. On Lake de Montigny, at the contact of the Pontiac series and the underlying greenstones, no conglomerate is found. The basal beds of the sedimentaries are dark mud rocks of the composition of a basic greywacke. Conglomerate does not occur here. Wilson describes the conglomerate as occurring in discontinuous patches. In the series of younger sediments to the north, already described by the writer, the conglomerate band at the base of the younger sedimentary series is always thick, strong, and continuous.

2. Wilson describes amphibolites occurring interbedded with the mica schists of the Pontiac series in places. Amphibolites were not observed by the writer to form part of any of the younger sedimentary series in any of the areas studied by him; they are, however, very characteristic of the Nemenjish series and form a considerable proportion of it.

3. Wilson[1] found outliers of the Grenville series (which, it will be shown, is probably correlative with the Nemenjish series) on Grand Lake Victoria, about twenty-five miles south of the most eastern outcrop of the Pontiac series. Bancroft[2] in 1916 found outliers of the Grenville series as far west as Doucet, some thirty miles

[1] *Geol. Surv. Can., Sum. Rept.*, 1912, p. 337.

[2] Personal communication

east of the most eastern outcrop of the Pontiac series. The intervening distance has not been closely examined. It seems strange that the Grenville series should approach the Pontiac so closely and yet not be found within the Pontiac area, and that so widespread a series as the Pontiac should end so sharply, and no further trace of it be found included in the granites to the south or east. Both these difficulties would at once disappear, however, if at least a part of the Pontiac were identical with the Grenville series.

4. To the north of the main belt of the Pontiac series Wilson has mapped several minor areas of sediments surrounded by the Abitibi volcanics. They are of mica schist only, without the conglomerate member. If the conglomerate and all the mica schists form a part of the same series, the conglomerate member should appear in these areas also, along the line of contact of the greenstones and the sediments.

In view of these facts the writer tentatively advances the view, alternative to that suggested by Wilson and Bancroft, that the so-called Pontiac series consists of two sedimentary series. The older, composed mainly of mica schists and amphibolites, is equivalent to the Grenville and Nemenjish series and may lie upon the older volcanic series conformably. The younger contains the conglomerate, arkose, and greywacke members, and perhaps a portion of the mica schists, and may be equivalent in age to the Mattagami, Broadback, Lucky Strike, and Brock series.

The rocks of the volcanic complex underlying the Pontiac series consist mainly of lavas varying in composition from basalt to rhyolite; the types of intermediate composition are the most common. Interbedded with them are small amounts of slate or slaty tuff, and dolomite, which in part at least is an altered rhyolite. Intrusive into these rocks are bodies of gabbro and diabase. All of the rocks have undergone more or less metamorphism and have been converted locally into schists. Outcrops throughout the area are too sparse to determine structure and succession, but wherever strikes are determinable they have a general east-west direction.

Summary.—The geological sections described in the foregoing areas may be summarized as follows:

Pontiac Area

Mica schist Arkose, greywacke Conglomerate Unconformity Basalt, andesite, rhyolite, tuffs, and intrusives	or	Mica schist Arkose, greywacke Conglomerate Unconformity Mica schist and amphibolite Basalt, andesite, rhyolite tuffs, and intrusives

Matlagamie Area

Mica schists
Conglomerate
Uncomformity
Basic intrusives
Basalts, andesites
Basalts, andesites, rhyolites, tuffs

Kenoniska Area

Mica schists
Quartzite
Arkose
Conglomerate
Unconformity
Garnetiferous mica schists
Slaty tuffs
Andesites
Basalt

Lucky Strike Area

Mica schist
Arkose, greywacke
Conglomerate
Unconformity
Garnetiferous mica schist
Tuffs, basalts, basic intrusives

Brock Area

Mica and hornblende schists
Grits
Conglomerate
Unconformity
Basalts and schists

Windy Lake Area

Tuffaceous sediments
Rhyolite porphyry
Flows of intermediate composition
Andesite flows
Basalt flows

Kaopatina–Nemenjish Area

Interbedded garnetiferous and non-garnetiferous mica gneisses and hornblende gneisses, with crystalline limestones
Non-garnetiferous mica gnesises
Interbedded mica gneisses and basic tuffaceous sediments
Basalt flows

Eau Jaune–Obatogamau Area

Fragmental rhyolite
Andesite tuffs
Andesite flows
Basalt flows

Father's Lake Area

Basic tuffs
Andesite flows
Porphyritic basalt flows
Basalt flows

Opawika Area

Rhyolite flows
Intermediate lavas
Andesite tuffs
Andesite flows

[*To be continued*]

A CONNECTING LINK BETWEEN THE GEOLOGY OF THE NORTHERN SHAN STATES AND YUNNAN

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T. H. D. La Touche has described in detail the geology of the Northern Shan States west of the Salween River and up to latitude 23° north.[1] J. Coggin Brown has at one point extended this work farther north, having thoroughly mapped the section between longitudes 97° 00′ and 97° 30′ and extending north to latitude 23° 15′.[2] But beyond this area north to the border of Yunnan the ground has not been studied by the Geological Survey of India. North of the border in Yunnan the broader details of the geological structure have again been studied and mapped by J. Coggin Brown and made available in various survey reports.[3]

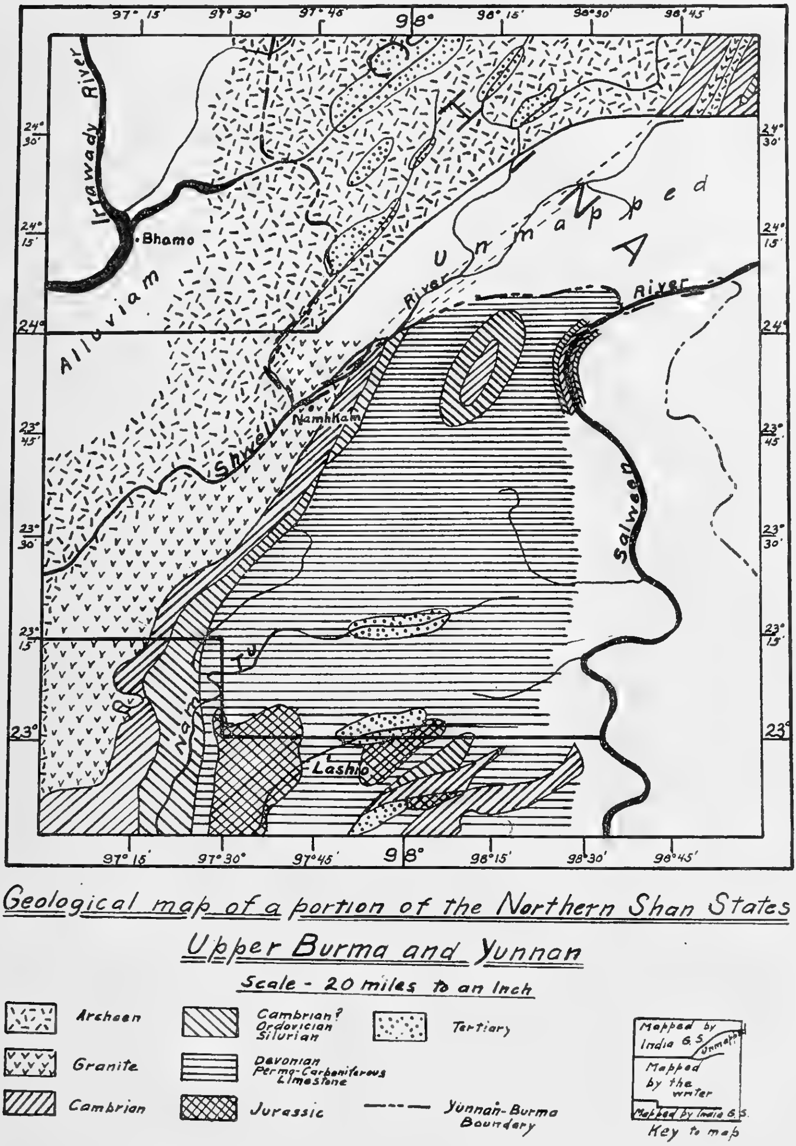
During the years 1917–18 the writer and several others, while doing exploration work for the Burma Mines, Limited, were enabled to take rough geological notes covering the unmapped area described above. By means of this work, as is shown on the accompanying map, the gap between the area in the South mapped by La Touche and Coggin Brown and that in Yunnan by Coggin Brown is partially filled in.

On the whole the section offers no points of marked difference from the areas to the south and north. Some slight differences between formations in Yunnan and the portions of the Northern Shan States familiar to him kept Coggin Brown from making definite

[1] T. H. D. La Touche, "Geology of the Northern Shan States, "*Memoirs of the Geol. Surv. of India*, XXXIX, Part 2.

[2] J. Coggin Brown, "Geology and Ore Deposits of the Bawdwin Mines," *Records, Geol. Surv. of India*, XLVIII, Part 3.

[3] J. Coggin Brown, "Contributions to the Geology of the Province of Yunnan in Western China: I, The Bhamo-Teng-Yueh Area," *Records, Geol. Surv. of India*, XLIII, Part 3, and other articles in the same series.



Geological map of a portion of the Northern Shan States Upper Burma and Yunnan

Scale - 20 miles to an Inch

correlations. The area described here helps to explain these differences and assists in correlating the two sections. Owing to the strictly economic purpose of our work in the field no attempt to gather fossils was made, and consequently the mapping was done on strictly lithological grounds. The various formations have, however, with the exception of the Ordovician and Silurian beds, such definite lithological characteristics that their determination can be safely made without recourse to fossils. The Ordovician-Silurian beds are not mapped separately but are shown as a single formation between the known older slates and quartzites and the younger Devonian-Carboniferous limestone.

TABLE I

List of Formations

Period	Name in the Northern Shan States and Character	Yunnan Equivalent
Recent, Subrecent	Alluvium—old river terraces—travertine	Nan Tien series
Tertiary	Clays—sandrock and brown coal	
Jurassic	Nam Yau series—red sandstones with limestone beds	
Permian, Carboniferous, Devonian	Plateau limestone—not differentiated into an upper and lower as by La Touche because of lack of fossil evidence	Permo-Carboniferous and older Paleozoic limestones
Silurian, Ordovician	Namhsim, Naungkangyi, and other Silurian and Ordovician beds of La Touche grouped because of lack of fossil evidence, shales, sandstones, and some limestone beds	Pu-Piao series
Ordovician, Cambrian?	Pangyun beds—not mapped by La Touche. Sandstones, shales, and occasional limestone beds	Possible transition beds between Kao-liang and Pu-Piao
Cambrian	Chaung Magyi—quartzites and shales	Kao-liang series
Archean	Mogok gneiss with limestone bands	Crystalline series. Gneiss, granite and mica schist with a few limestone bands of Brown
Igneous	Granite—intrusive into gneiss and Chaung Magyi but age unknown. Basic dikes—intrusive into the granite	

In Table I are given the formations present in the area discussed. The same names are assigned to them as are used by La Touche in his *Geology of the Northern Shan States*. In the right-hand column are given what appear to be the corresponding formations in Yunnan. The names are those given by J. Coggin Brown in his reports on that province.

TOPOGRAPHY

The main structural features are the high mountain region of the western section (some of the peaks being over 7,000 ft.) composed of granite, gneiss, and the older Paleozoic sediments, and the

more open, less accentuated, topography of the Plateau limestone over most of the eastern section.

The Shweli in the North and the Nam Tu in the South both flowing in a general southwesterly direction are the dominant streams, carrying off all the drainage of the area, with the exception of a narrow strip along the eastern edge, where the streams flow east into the Salween. The Salween flows almost due south and, as is characteristic of it for most of its course through Yunnan and Burma, it has cut its way down far below the surrounding country and consequently has a very limited lateral drainage. The streams flowing into the Salween in this section have a length rarely exceeding thirty miles. Notwithstanding this fact it far exceeds any of the other streams in volume of water.

The abrupt change in the character of the country at the contact between the older Paleozoic sediments and the younger limestones is most pronounced, the former rocks standing up as a rampart across the whole area. In the isolated oval-shaped exposure of these rocks in the northeast corner of the Northern Shan States the same conditions hold, the older sediments rising up as a rugged, intricately dissected network of mountains out of the surrounding limestone country, which, by comparison, is of moderate relief, with wide valleys and rounded hills. The characteristic underground drainage of the limestone area has given rise to large sections, in which the topography consists of numerous sink holes of all sizes, inclosed basins in which the drainage disappears into the limestone. The same characteristic has also produced peculiar local topographic forms, such as hanging valleys without visible outlets and valleys with two distinct valley floors at different levels.

Certain sections of the granite area, in which the rock is of an extremely coarse-grained homogeneous nature, have weathered into a multitude of small, rounded hillocks without any definite drainage system. The streams wind sluggishly through the maze of small hills, often forming marshy lands. In this section the granite has weathered *in situ* often to a depth of several feet, leaving a soil composed of all the constituents of granite arranged in their normal position but unconsolidated.

ARCHEAN SYSTEM

The Mogok gneiss in this area is similar in every way to this rock as described by Barrington Brown and J. W. Judd in the Ruby Mines district and Coggin Brown in his traverse from Bhamo in Burma to Teng-Yueh in Yunnan. Consequently the section mapped here allows one definitely to connect those two areas. The gneiss is present in a great variety of types and often assumes both schistose and granitoid forms. All phases, from extremely acidic to basic hornblende gneisses, are found. Bands of coarsely crystalline limestone are present, as in the other areas of this rock. In fact, this band of igneous and metamorphic rocks maintains a great regularity in its diversity, whether examined far to the south of Mandalay (east of Pyawbwe in latitude 20° 40′) or in the North at Teng-Yueh in latitude 25° 00′. Noteworthy at widely separated points are the crystalline limestone beds. These limestones are of considerable interest, first in that they house an extremely varied collection of minerals, over twenty-five mineral species having been identified by Barrington Brown and Professor Judd, and secondly in that Professor Judd has argued in favor of the inorganic origin of the limestone by means of the alteration of the unstable scapolite contained in the basal gneisses. It would appear that the practical continuity of this crystalline limestone, in a well-defined zone more than two hundred and fifty miles in length is almost conclusive evidence of its original organic origin.

GRANITE

The granite is discussed at this point because, although considerably younger than the gneiss, being in fact intrusive into the Cambrian sediments, it is always found either entirely within the gneiss or along its eastern edges. On the map no attempt is made to show the granite areas within the gneiss. There are, however, no grounds for not believing that the large mass of homogeneous granite shown as occurring between the gneiss and the older sediments is not genetically the same as the very numerous bodies of granite found entirely within the gneiss area. The granite is a normal biotite granite and extremely consistent in its mineral character over large areas; extreme variations occur, however, in the texture from coarse-grained to fine-grained types. Intrusive

dikes of a basic type are common and in some localities cover an extensive area.

Coggin Brown in his work in Yunnan did not attempt to map the granite separately from the gneiss, but from the text it appears very probable that the band of granite separating the gneiss from the younger sediments south of the Shweli extends well north of that river into Yunnan.

The peculiar type of topography and accompanying excessive disintegration over a portion of the granite area has been mentioned previously.

CAMBRIAN (CHAUNG MAGYI)

These rocks differ in no respect from the descriptions of them in the neighboring sections, as given by previous writers. They consist of slaty shales, phyllites, and quartzites, severely folded and of rapidly varying strike. The band of rocks of the Kao-liang series mapped by Coggin Brown in Yunnan just east of the Shweli River in latitude 24° 40′ is undoubtedly a direct continuation of the Chaung Magyi of the Northern Shan States.

LATE CAMBRIAN-ORDOVICIAN-SILURIAN BEDS

These formations are all grouped together, as it is possible to separate them only by careful paleontological work. The oldest rocks of this group are of the most interest, as it is in the section under discussion that they attain their greatest importance. They have been called the Pangyun beds by Coggin Brown. No fossils have been found in them, but as they are conformably followed by Ordovician beds they are themselves either late Cambrian or early Ordovician.

It has been generally assumed by other observers that a decided break exists between the non-fossiliferous Chaung Magyi and the fossiliferous Ordovician strata, but it seems possible that this may have been due to the fact that favorable exposures of the intervening rocks had never been observed. In this area numerous sections were examined from the Chaung Magyi to the Silurian rocks, and no decided break could be found, the Pangyun beds apparently filling in the period between the Chaung Magyi and the fossiliferous Ordovician. In this connection it is interesting to note that limestone beds are present at various points in the Pangyun series.

Coggin Brown in discussing the Kao-liang system states that "lower down the eastern slope of the divide (Irrawady-Salween), silver-grey phyllites are interbedded with dark slates and bands of limestone. In the latter occurrence there is a marked difference from the Chaung Magyi system of the Northern Shan States, which otherwise they greatly resemble, for the former system does not contain lime in any form." On the assumption that the Pangyun beds are a transition series between the Chaung Magyi and the younger fossiliferous beds it is possible that the beds observed by Coggin Brown belong to this series and thus represent the passage from the Kao-liang system to the Pu-Piao series.

The younger Ordovician and the Silurian beds closely resemble those described by La Touche for the area to the south. They consist of sandstones, shales, marls, and occasional limestone beds. A detailed study of these beds in this section, with careful paleontological work, would undoubtedly allow of their being separated into their smaller subdivisions, as has been done by La Touche for the rest of the area.

The Pu-Piao series and the Silurian system in Yunnan of Coggin Brown are assumed as being analogous with the group of beds mapped here as lying between the Chaung Magyi and the younger limestones, with the slight difference that the bottom member (Pangyun beds) may belong both to the Kao-liang and the Pu-Piao.

DEVONIAN-CARBONIFEROUS-PERMIAN (PLATEAU LIMESTONE)

It has not been attempted to differentiate this formation, which covers a period from the Devonian to the Permian, into an upper and lower, as has been done by La Touche in the southern area. It is a direct continuation of the Plateau limestone mapped by him, and similar to it in all respects. In all the eastern section of the area it completely covers the older rocks except at two points, one in the northeast corner, where an eroded anticlinal mass has exposed the older sediments down to the Chaung Magyi, and the second in the gorge of the Salween, which river has cut its way down through the limestone and Silurian and Ordovician sediments into the Cambrian. At neither of these points are igneous or metamorphic rocks exposed.

As shown, this broad band of limestone continues into Yunnan and is thus directly correlated with the Devonian and Permo-Carboniferous limestone of that province.

JURASSIC (NAM YAU BEDS)

At one point in approximate latitude 23° 47′ longitude 98° 15′ on the flanks of the dome-shaped anticline in which the older sediments are exposed, beds of coarse conglomerates, with the pebbles largely of limestone, were noted. A short distance from this point extensive beds of red sandstone were encountered lying above the Plateau limestone. Their position and character are fairly strong evidence in assigning them to the Nam Yau, but the scant opportunity for examining them makes their definite determination unadvisable. This is especially true as they also resemble the Red Bed series of Yunnan (Permian-Triassic), as described by Coggin Brown, and may possibly represent a southern outlier of those beds.

No Jurassic beds have as yet been identified in Yunnan.

TERTIARY

Fairly extensive deposits of Tertiary beds are present in the Nam Tu valley, but they were not noted elsewhere, although it is possible that small remnants are present in some of the other valleys in the Plateau limestone. They are found as unconsolidated sands and clays and often contain extensive deposits of lignite and sub-bituminous coal.

RECENT

All the more prominent river valleys are covered with deposits of recent alluvium, probably with the exception of the Shweli valley in the Namhkam area, always of fluviatile origin. In the case of the Shweli valley the broad plain about thirty miles long, with an average width of five or six miles, probably represents an old lake bed similar to the numerous ones which have been noted in Yunnan. Recent elevation with consequent renewed erosion by the Shweli has largely concealed its former character.

It has not been attempted to show these deposits on the accompanying map, as it only tends to confuse the relations of the underlying consolidated formations.

ON THE ACCURACY OF THE ROSIWAL METHOD FOR THE DETERMINATION OF THE MINERALS IN A ROCK

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Some years ago Julien[1] expressed a doubt as to the accuracy of the Rosiwal method in the determination of the percentage composition of rocks in general. He thought, if the fragments were equicubical, that d, the measured average diameter of the mineral plates, might give correct results, but for unequicubical grains the value d^3 should be used, and for rounded grains,[2] thick lenses, or short spindles, $.7854\sqrt{a}$ or d^2. For schistose rocks with flakes and interlaminae parallel and of equal thickness, he suggested d^2, for prisms or blades with parallel interlaminae, $d'=\sqrt[3]{l\times b\times t}$, where l, b, and t are the length, breadth, and thickness of plates.

Williams,[3] several years later, studied the comparative accuracy of various methods, using a pink granite from Westerly, Rhode Island, with grains ranging from 1.5 to 5 mm. in diameter. Several determinations were made in each experimental method and the results were averaged and tabulated with the calculated results as shown in Table I.

The first column is calculated from the chemical analysis and is practically the norm, except for the small amount of biotite. The second column represents the percentages of the different minerals obtained by separation according to their specific gravities in Sonstadt's solution. The agreement of this determination with the preceding is fairly close. The third column is based upon

[1] A. A. Julien, "Genesis of the Amphibole Schists and Serpentines of Manhattan Island, New York," *Bull. Geol. Soc. Amer.*, XIV (1902), 460–68.

[2] Julien gives $.7854\sqrt{a}$ or d^2 for this value. Williams gives $.5236d^3$, the volume of a sphere, as Julien's (possibly later) figure.

[3] Ira A. Williams, "The Comparative Accuracy of the Methods for Determining the Percentages of the Several Components of an Igneous Rock," *Amer. Geol.*, XXV (1905), 34–46.

microscopic measurements of the diameters of grains in thin section made according to the Rosiwal method, the results thus obtained being multiplied by the respective specific gravities to give weight percentages. (Personally the present writers prefer to transfer the specific gravity determinations into volume percentages rather than the reverse, since one estimates the composition of a rock by volumes and not by specific gravities.) The fourth column represents six different photomicrographic prints, made of different parts of the slide, which were dissected and weighed according to the Delesse-Sollas-Joly method. The weights of the fragments of paper were assumed to be proportional to the areas, therefore to the

TABLE I

	I Calculated from Chemical Analysis	II Heavy Solution	III Measurements of Diameters Rosiwal Method	IV Photomicrographs of Areas	V Areas (d^2) Measured by Microm. Ocular	VI Calculations of d^3 from Column III	VII Calculations of d^3 from Column V
Quartz	35.90	34.25	19.02	23.23	19.90	1.41	12.14
Orthoclase	34.48	32.47	43.65	43.64	43.67	56.04	49.92
Plagioclase	24.99	26.91	32.90	32.90	32.90	42.24	37.31
Mica	0.26						
Magnetite	2.60	5.68	4.43	0.25	3.52	0.31	0.63
Hematite	1.10						

volumes of the minerals. The percentages were computed as before. The fifth column represents measurements of areas made by means of a net-micrometer ocular, as originally used by Rosiwal; the number of squares included within the boundaries of the different minerals being counted. The areas again were assumed to be proportional to volumes. The sixth column was obtained by cubing the values in column III and reducing the sum to 100. The last column represents d^3 calculated from the value of d^2 in column V.

Williams pointed out the close agreement between the composition calculated from the chemical analysis and the results obtained with Sonstadt's solution on the one hand, and that obtained by the Rosiwal method and the measurement of areas on the other. The two sets of values, however, do not agree. He remarked that "though the absolute volumes (of the microscopic methods) may not be correct, using *d* as indicated, relative volumes as expressed

in percentages may nevertheless give as significant results as if the actual value of d were known." The results of columns VI and VII indicate that d^3 cannot be used for calculating the percentage composition when d is the measured width of the mineral grains in the thin section.

Williams concludes that

any one of the direct measurements with the microscope does not appear to fulfill even approximately the necessary conditions for a statement of the complete quantitative composition," but that "heavy solutions are a convenient and readily applicable method of separating the minerals of a rock and may be valuable in determining quantitative relations. . . . . The accuracy of the results will be directly proportional to the coarseness of grain and the readiness with which the minerals can be separated.

So far as the writers are aware, no other comparisons have been made between the specific gravity method and that of Rosiwal. Contrary opinions to those just quoted are held by many petrographers. Thus in Table II we have the comparison of a

TABLE II

	I Calculated Composition from Analysis	II Rosiwal Volume Analysis: First Specimen	III Weight Percentage: First Specimen	IV Rosiwal Volume Anal.: Second Specimen	V Weight Percentage: Second Specimen
Quartz	22.86	23.17	22.55	20.97	20.34
Orthoclase	18.35	18.62	17.57	21.07	19.82
Ab_3An_2	39.74	43.10	42.47	42.29	41.48
Biotite	10.92	8.87	9.77	8.15	8.94
Hornblende	3.56	3.78	4.44	4.84	5.67
Pyroxene		1.97	2.37	2.07	2.50
Magnetite	1.86	.40	.76	.54	1.02
Pyrite, etc.	1.86	.04	.07	.02	.04

computation from chemical data of mineral composition with measured linear dimensions according to the Rosiwal method made by Cross, Iddings, Pirsson, and Washington[1] for the Butte "granite."

In Table II, columns I, III, and V should be compared. The authors state that a small amount of pyroxene was intergrown with

[1] Cross, Iddings, Pirsson, and Washington, "A Quantitative Chemico-Mineralogical Classification and Nomenclature of Igneous Rocks," *Jour. Geol.*, X (1902), 681–82. *Ibid.*, *Quantitative Classification of Igneous Rocks* (Chicago, 1903), p. 286.

the hornblende and was probably included in the analyzed hornblendic material. The two minerals are, therefore, calculated together. There can be no question about the success of the Rosiwal determinations in this case. Cross, Iddings, Pirsson, and Washington[1] say: "It is possible . . . . to determine very closely the proportions of the minerals present. . . . ." This determination proves either the accuracy of the Rosiwal method or, since it is only a single example, an almost exact compensating error.

Among other petrographers who have found the microscopic methods of sufficient accuracy are Barrell,[2] who determined his constituents by a somewhat simpler, though less accurate, method. He says:

The field of view of the microscope is divided into quadrants by the cross-hairs, and these are mentally divided into sectors which are thirds, fifths, or smaller fractions. By taking such a power of objective that the component to be estimated is represented in the field of view by a fair number of crystals, the latter can be mentally collected together and packed into one quadrant, and the fraction which it fills estimated. . . . . In the case of holocrystalline rocks, where the writer has been enabled to check this method of estimating the mineral and chemical composition by comparison with laboratory analyses, *it is found that the error in any one element should be less than 1 per cent and is often less than one-half per cent.* [The italics are ours.]

Robinson[3] compared the Rosiwal measurements of a porphyritic dacite with the composition calculated from an analysis and found that

there is a difference of 3.2 per cent between the total salic components, including the excess of alumina in the calculated mode, and of 2.6 per cent between the dark components. . . . . The comparison will give an idea of the accuracy of the Rosiwal method as applied to porphyritic lavas containing small amounts of minerals of highly variable size.

Tyrrell[4] says:

The graphic method of quantitative mineral measurement invented by Rosiwal yields sufficiently accurate results for classificatory purposes in the

[1] *Ibid.*, p. 204.

[2] Joseph Barrell, "Microscopical Petrography of the Elkhorn Mining District, Jefferson County, Montana," XXII An. *U.S. Geol. Surv.*, Pt. II, 1901, pp. 512–13.

[3] Henry Hollister Robinson, "The San Franciscan Volcanic Field, Arizona," *U.S. Geol. Surv., Prof. Paper 76*, 1913, p. 121.

[4] G. W. Tyrrell, "A Review of Igneous Rock Classifications," *Science Progress*, 1914, pp. 74–75.

great majority of types. . . . . Notwithstanding the opinion of Williams, the Rosiwal method of estimation is capable of giving extremely accurate results. The writer . . . . has found the chemical composition calculated from the results of the Rosiwal measurements to be strikingly accordant with that obtained by ordinary chemical analysis.

In view of Williams' apparently careful study and rejection of the Rosiwal and other microscopic methods, and of the increasing use made of volumetric determinations of rock constituents by other petrographers, it was thought desirable to repeat the experiments with all possible precautions against errors in both the Rosiwal and the heavy solution methods. Williams' study is apparently the only one in which there was a comparison of the percentages determined by the microscopic measurement method and an actual separation of the minerals; all others are comparisons between the former and recalculated chemical analyses, with all the possible errors in allotting constituents due to the uncertain composition of the dark constituents and the possible soda content of the orthoclase.

The material chosen for the experiment by the present writers was the Butte "granite." It was selected because it had been chemically analyzed, because there was available ample material from the original locality, and because there were on hand six thin sections and the two determinations by the Rosiwal method made by others as mentioned above, and five determinations by students on one slide (Table III, column I). Furthermore, the material is of fairly uniform grain and composition in widely separated localities, thus giving a fairer test than would a rock differing possibly in different sections and thus probably different from the material analyzed.

The six different sections were measured by the Rosiwal method from one to five times each, fourteen determinations being made in all. The average of each slide, reduced to weight percentages, is shown below. In Table III the first six columns represent the six sections; the number in parentheses after each indicates the number of times it was measured. The seventh and eighth columns are the determinations taken from Cross, Iddings, Pirssons, and Washington and quoted above. The variations between the read-

ings obtained for the different sections are possibly due to differences in the sections themselves, the grain of the rock being coarse enough to show slight variations. The last column shows the average of the sixteen determinations, and not the average of the averages.

TABLE III

	I (5)	II (1)	III (2)	IV (3)	V (1)	VI (2)	Cross, Iddings, Pirrson, and Washington		Average
Quartz	20.31	22.4	23.79	24.76	20.3	17.64	22.55	20.34	21.6
Orthoclase	25.31	31.6	18.15	30.77	28.5	29.11	17.57	19.82	25.8
Plagioclase	38.75	32.9	43.00	25.18	32.3	32.01	42.47	41.48	35.6
Biotite	8.98	8.3	8.35	9.70	10.8	10.47	9.77	8.94	9.2
Hornblende	4.65	4.4	5.81	7.02	5.2	7.47	4.44	5.67	5.6
Augite	.70	.2	......	1.01	1.3	2.76	2.37	2.50	1.1
Magnetite	.74	......	.63	1.50	1.2	.58	.76	1.02	.8
Apatite	.03	.1	.10	......	......	......	......	......	.0
Titanite	.04	......	.09	......	......	......	......	......	.0
Pyrite	.55	......	.04	......	0.3	.09	.07	.04	.2
Zircon	.03	......	......	......	......	......	......	......	......
	99.99	99.9	99.96	99.94	99.9	100.13	99.98	99.81	99.9

For the separation of the constituents by mechanical means, several methods were employed. The magnetite was first removed by means of an electromagnet.[1] By repeating the process the material removed was practically pure. The biotite was next separated by Rosenbusch's[2] method of shaking the rock powder from an inclined sheet of semi-glazed paper. A remarkably clean separation resulted as shown by microscopic examination, only a few flat hornblende flakes being included as impurities. The remaining material was now placed in a Brögger-Harada[3] tube with about a half-pint of Sonstadt's (potassium-mercuric-iodide) solution, and enough water was added to bring down the hornblende and augite. For the purpose of these experiments it was not necessary to separate these two minerals, so it was not attempted. With these minerals the zircon, apatite, and titanite came down. Thus far the separation was easy; the difference in color between the heavy minerals and those remaining clearly showed when

[1] The instrument is illustrated and the method described in Johannsen's *Manual of Petrographic Methods*, 1918, Fig. 725, and p. 540.

[2] *Ibid.*, p. 557. [3] *Ibid.*, p. 551.

the separation was complete. The separation of the plagioclase (Sp. gr. 2.68) from the quartz (Sp. gr. 2.65) was the most difficult. As an indicator, therefore, a small Herkimer County quartz crystal was placed in the solution, which was then diluted until the crystal began to sink, after which a very small amount of concentrated solution was added to make it slowly rise to the top. This adjustment between the specific gravity of the quartz and that of the liquid is here so delicate that a slight change in the density of the solution, such as results from a slight change in the temperature of the room, caused the quartz, which has a very small coefficient of expansion, to settle during the night and rise again during the day. When the equilibrium was established, the plagioclase was removed, washed, dried, and weighed as in the other cases. The quartz was brought down by adding enough water to bring down the indicator. The final material was the orthoclase.

The greatest objection to the specific-gravity method seems to be the impossibility of preparing powder which consists of homogeneous material. In many cases material of one kind will cling to grains of another and will increase or decrease their specific gravities. The small amount of mixed material shows up very clearly in the separation, especially when between light and dark minerals, for the mixed heavier grayish material will come down before the pure white mineral, or, on the other hand, the precipitated dark mineral will be covered with a thin layer of material that is grayish. The probabilities are that the two errors compensate. The material should be crushed fine enough to separate each constituent from every other, but not so fine as to produce dust, since some minerals pulverize much more readily than others and a different proportion of each will be lost, destroying the accuracy of the result. A happy medium must therefore be taken between purity and selective sieving, since absolute purity cannot be expected. Microscopic examination of a small amount of the material of a certain size will readily make it possible to determine whether or no the rock has been crushed fine enough to produce a good separation of the constituents. For the following experiments various-sized grains were used, as indicated at the top of each column in Table IV. After crushing and sifting, the total samples weighed

140–150 gms. This was quartered, and one-fourth of each quarter was used to make two samples for determination. For this particular rock, grains passing through a 60-mesh sieve and remaining on a 100 mesh seemed to be very suitable.

TABLE IV

	I Sp. gr.	II Mesh 80–100	III Mesh 80–100	IV Mesh 60–100	V Mesh 60–100	VI Mesh 60–100	VII Mesh 60–100	VIII Average
Magnetite	5.10	1.38	1.09	1.42	1.12	1.36	1.30	1.26
Biotite	3.00	11.10	9.49	9.94	9.74	9.88	9.72	9.98
Hornblende / Augite	3.20 / 3.30	6.66	6.93	6.66	6.44	6.31	6.25	6.54
Plagioclase	2.68	37.87	37.10	34.60	31.65	32.82	33.40	34.57
Quartz	2.65	19.21	21.11	21.35	23.22	24.65	23.70	22.21
Orthoclase	2.57	23.07	24.25	26.00	27.06	25.02	26.06	25.25
		99.29	99.97	99.97	99.23	100.04	100.43	99.81

Comparing now the final results of each of the three methods, we have the results given in Table V.

TABLE V

	Calculated from Analysis	Weight Percentage Rosiwal	Heavy Solution
Quartz	22.86	21.6	22.21
Orthoclase	18.35	25.8	25.24
Plagioclase	39.74	35.6	34.57
Biotite	10.92	9.2	9.98
Pyribole	3.56	6.7	6.54
Magnetite	1.86	.8	1.26
Pyrite, etc.	1.86	.2	....
	99.15	99.9	99.83

The amount of quartz in the calculated analysis is practically the same as in the specific-gravity determination, and the Rosiwal value is only slightly less.

The orthoclase is low in the calculated analysis and practically the same in columns 2 and 3, while the calculated plagioclase is high as compared with the other two determinations. This is unquestionably due to the fact that the orthoclase carries soda. In the computation of the analysis by Cross, Iddings, Pirsson, and

Washington (p. 225), orthoclase was taken as $K_2O \cdot Al_2O_3 \cdot 6SiO_2$ in the place of the actual composition. In all probability the orthoclase-plagioclase percentages of the Rosiwal and specific-gravity determinations are more nearly those of the actual minerals present than those computed from the chemical analysis. It will be seen that the sums of the feldspars, 58.09, 61.4, and 59.81, are not greatly different.

The sums of the leucocratic constituents in the three columns, 80.95, 83.00, and 82.02, are also close together, as are the biotite and magnetite values.

The only noteworthy variations in any of the determinations are in the values of the remaining constituents—the pyribole and the pyrite. Here the values for the former are 5.42, 7.5, and 6.54, and for the latter, 1.86, 0.3, and 0. For the sum of the two constituents in each column, however, we have 7.28, 7.8, and 6.54. In the first place the sum of all the constituents in the analysis calculated by Cross, Iddings, Pirsson, and Washington in column 1 is only 99.15, as against 99.9 and 99.81 in the other two columns; consequently the first-column values should be slightly increased. The calculated amount of pyrite (1.86) is greatly in excess of that seen in any slide or in the hand specimen. The fraction of 1 per cent given by the thin section is much more nearly correct. When the greater part of the pyrite is added to the pyribole in column 1, the values are more nearly the same. In the specific-gravity determination the magnetite and biotite were removed before the pulverized material was placed in the Sonstadt solution, which was then diluted until the pyribole and the small amounts of pyrite, apatite, and zircon present came down. Therefore these latter minerals are included with the pyribole in that column. The rock analysis and the thin sections were clearly from material slightly more melanocratic than the pulverized rock used in the specific-gravity determination, as is shown by the difference between the leucocratic-melanocratic ratio of columns 1 and 2 as against column 3.

Reviews

Manual for the Oil and Gas Industry under the Revenue Act of 1918. By the U.S. Bureau of Internal Revenue of the Treasury Department, 1919. Pp. 136, figs. 13.

To assist the taxpayer of the oil and gas industry in correctly and expeditiously preparing his Federal tax returns, the Bureau of Internal Revenue has prepared a "Manual for the Oil and Gas Industry Under the Revenue Act of 1918." Although the endeavor has been made to anticipate all questions that may be asked regarding the law and regulations, and the latter have been amplified when it was deemed necessary to obtain the desired result, it is recognized that such a manual is only general, and cannot cover all cases that may exist. The *Manual* is based largely upon information gathered during the fall of the year 1918 by a corps of geologists, technologists, and engineers. The investigation was undertaken primarily to furnish a basis for arriving at valuations, and depletion and depreciation deductions, in connection with oil and gas properties.

The *Manual* (136 pages and 13 plates) is now being distributed among taxpayers of the oil and gas industry. For the purposes of the *Manual*, the country is divided into seven districts, each of which was handled by a supervisor and several assistants. These are: (1) the Appalachian Field, (2) the Lima-Indiana and Illinois fields, (3) the Mid-Continent Field, (4) the Northern Louisiana Field, (5) the Gulf Coast Field, (6) the Rocky Mountain District, and (7) the California Field.

The book consists of three parts: *Part I* deals directly with the Law and Regulations, *Part II* with the question of depreciation, and *Part III* consists of descriptions and methods of estimating underground oil reserves, especially by means of production curves. A collection of curves and tables covering many of the oil fields and pools in the United States accompanies the text. They are intended as a suggestion for the guidance of the taxpayer in the computation of his depletion allowance.

The work of compiling and editing the material in the *Manual* was done largely by A. D. Brokaw, J. L. Darnell, and L. G. Donnelly. The investigations leading to the preparation of the *Manual* and its compilation and publication were under the general supervision of Ralph Arnold, Chief of the Oil and Gas Section.

Copies may be obtained by application to the Commissioner of Internal Revenue, Washington, D.C.

Map 1677. Coleraine, Quebec. Geology. [Canada Department of Mines, Geological Survey. Ottawa, 1917.]

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VOLUME XXVII NUMBER 4

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

MAY-JUNE 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, LONDON AND EDINBURGH
THE MARUZEN-KABUSHIKI-KAISHA, TOKYO, OSAKA, KYOTO, FUKUOKA, SENDAI
THE MISSION BOOK COMPANY, SHANGHAI

May-June 1919 Vol. XXVII, No. 4

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

The following are authorized to quote the prices indicated:

For the British Empire: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, 18*s*. 8*d*. each; single copies, including postage, 3*s*. 2*d*. each.

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Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit. Deliveries are not guaranteed within the war zones of Europe, nor in other countries where transportation is disturbed by conditions incident to war.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Separates, if desired, must be ordered in advance of publication. Separates of leading articles will be printed as ordered, of which 50 (without covers) will be furnished *gratis*, the actual cost of the remainder (and covers, if desired) to be paid for by the author. The actual cost may vary, and will depend upon the amount of work in remaking the pages into forms, presswork, paper, binding, etc. Separates containing half-tones may be expected to cost somewhat more, the increase depending upon the number of cuts and the amount of work required upon them.

Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918

Among articles to appear in the early numbers of *The Journal of Geology* are the following:

The Geology of Florida. By E. H. SELLARDS.

One of a series of articles appearing from time to time, giving a summary of the geology of the various states, illustrated by maps and the geological column shown by well records.

Inequalities of Sedimentation. By E. M. KINDLE.

Contains pertinent and valuable material on the phenomena of sedimentation.

Pre-Cambrian Rocks of Southeast Newfoundland. By A. F. BUDDINGTON.

The Richardton Meteorite. By T. T. QUIRKE.

Investigation versus Propagandism. By T. C. CHAMBERLIN.

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THE

JOURNAL OF GEOLOGY

MAY-JUNE 1919

THE BUILDING OF THE COLORADO ROCKIES

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The University of Chicago

PART II

THE LYONS-GRAND RIVER SECTION

After a consideration of alternative locations for the contemplated study of the Colorado Rocky Mountain diastrophism, a section across the folded belt between the Great Plains north of Denver and the Uinta Basin west of Glenwood Springs was selected as offering the most promise. Among the advantages thus offered, it may be noted that this section would bring in the characteristic *en échelon* structure of the eastern foothills, here specially declared;[1] it would cross the Front Range where strongly developed; it would embrace the wide area of sedimentary rocks in Middle Park; it would traverse a typical section of the Park Range, and finally beyond this it would extend across the most representative strip of the slightly disturbed sedimentary belt to the Grand Hogback which terminates the Rocky Mountain folding on the west. Such a section, furthermore, would be across one of the wider portions of the Colorado Rockies. There was a further advantage growing out of the fact that the Colorado Rockies

[1] This has recently been described by Victor Ziegler, "Foothills Structure in Northern Colorado," *Jour. Geol.*, XXV (1917), 715-40.

embrace extensive areas of pre-Cambrian granite and other crystalline rocks. Over such areas of old crystalline rocks it is difficult to reconstruct the folds, since these areas afford only the most meager information as to the nature of the post-Cretaceous folding and as a result are little better than blank pages in the later diastrophic story. It was therefore advisable to choose a section which, though it be typical of the mountain system as a whole,

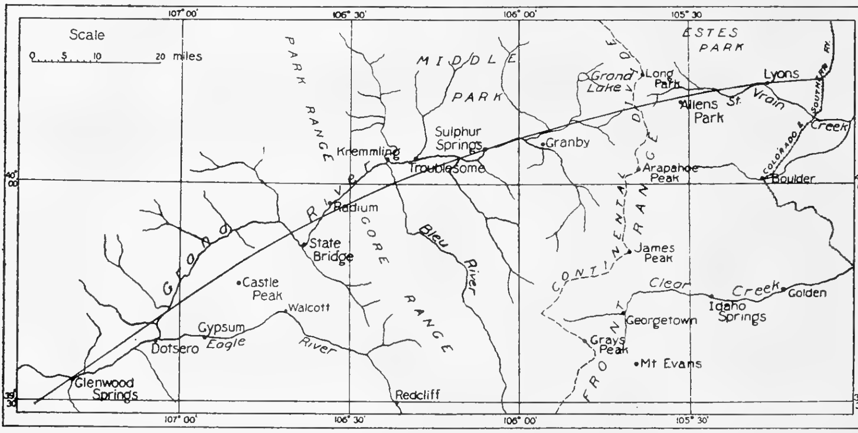

FIG. 4.—Map of the Lyons–Grand River section. The section extends along a curved line from the Colorado and Southern Railroad east of Lyons, to the western slope of the Grand Hogback southwest of Glenwood Springs, a total distance of 135 miles. Because of the adopted curvature the line of the section crosses the axial lines of the folds approximately at right angles.

still crossed the granite belts where they are narrowest, and where the belts of folded sedimentary rocks are widest. This was accomplished in the section chosen.

The section finally selected for measurement has as its eastern terminus the bend of the Colorado and Southern Railroad tracks, 4½ miles north of the town of Longmont (Niwot sheet, T. 3 N., R. 69 W., Sec. 11, middle of S. line). From this point westward the line of section was drawn so as to strike the bench mark (5,375 feet) in the town of Lyons, to pass onward through Allen's Park, and across the continental divide one-fifth of a mile north of Oglala Peak (13,147 feet). On the Pacific slope it continues west-

ward in the general vicinity of the Grand River, runs by the railroad station at Hot Sulphur Springs, passes $2\frac{1}{3}$ miles north of State Bridge, and finally crosses the city of Glenwood Springs and the

FIG. 5.—Lyons sheet (No. 1) on the east and St. Vrain sheet (No. 2) on the west. The restored folds include all beds to the top of the Laramie. The principal formations are: (1) pre-Cambrian granite; (5) Fountain and Lyons sandstones; (6) Lykens (red beds); (7) Morrison; (8) Dakota; (9) Benton and Niobrara; (10) Pierre; (11) Fox Hills and Laramie. The layers have been left unshaded throughout a horizontal strip whose base represents a level 5,000 feet above the sea, and whose top is the tilted peneplain surface. The profile of the present land surface is represented by a line which lies for the most part within this unshaded strip. Each sheet represents a horizontal distance of ten miles.

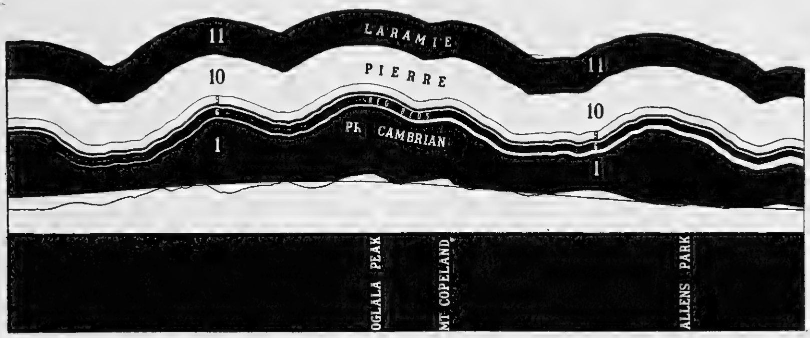

FIG. 6.—Allen's Park sheet (No. 3) on the east and Continental Divide sheet (No. 4) on the west. The peneplain here reaches its greatest elevation. A few monadnocks rise above the bowed peneplain and today constitute the high peaks of the Front Range. Fig. 6 represents a horizontal distance of twenty miles.

Grand Hogback to the flat-lying strata of the Uinta Basin, $6\frac{1}{4}$ miles southwest of Glenwood Springs (Fig. 4).

The trace of this section drawn on the map is not a straight line, for it was purposely given a slight curvature that it might cross

the trends of the different folds as nearly at right angles as possible. This curvature was necessitated by the fact that the individual ranges are not parallel to one another, but converge toward the south. The curved section crossing these ranges at right angles, and hence also normal to the axial lines of the folds, has its convex

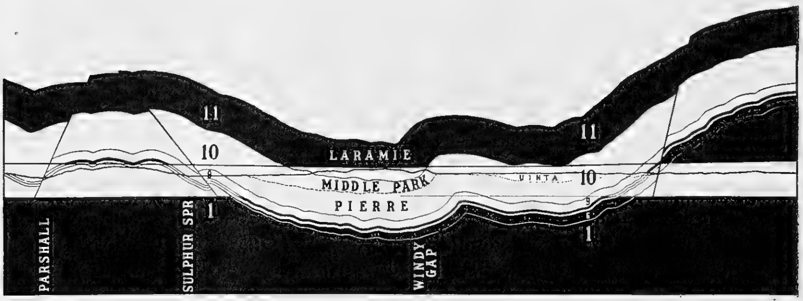

FIG. 7.—Granby sheet (No. 5) on the right and Sulphur Springs sheet (No. 6) on the left. The Middle Park (early Tertiary) beds occupy a part of the structural basin between Windy Gap and Sulphur Springs while the Uinta beds appear in the lesser basin in the middle of the Granby sheet.

FIG. 8.—Troublesome sheet (No. 7) on the east and Gore Range sheet (No. 8) on the west. The formations are: (1) pre-Cambrian granite; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Colorado and Pierre; (11) Fox Hills and Laramie. Basin of Uinta beds in the middle of the Troublesome sheet. The peneplain rests upon the broad crest of the Gore Range.

side therefore facing northwest. The total length of the section measured on this slight curve is 135 miles.

The topographic sheets of the United States Geological Survey as yet cover only the eastern portion of this selected section. Here the Niwot, Boulder, and Long's Peak sheets were a great help in locating the field observations and in plotting the cross-section. West of

the Long's Peak quadrangle, one had to be satisfied with the land surveyor's map of Grand County and the Department of Agriculture's Forest Service map of the Holy Cross National Forest, which together cover the remainder of the section.

Throughout this section of 135 miles, the dips of the strata were read wherever obtainable, and were plotted to scale as the

FIG. 9.—State Bridge sheet (No. 9) on right and Castle Peak sheet (No. 10) on left. Formations: (1) pre-Cambrian; (2) Sawatch; (4) Blue limestone; (5) Weber and Maroon formations; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde.

FIG. 10.—Gypsum sheet (No. 11) on the right and Dotsero sheet (No. 12) on the left. The peneplain level appears high above the present surface because this section is within the Grand River Valley. Conventions as before.

basis for the reconstruction of the original folded structure. Compared with the Pennsylvania Appalachians, the Colorado Rockies present greater obstacles to an investigation of this sort, because it is impossible to obtain equally complete data. In the Appalachians of Pennsylvania the sedimentary beds still persist throughout the mountainous region to such an extent that from the remnants the original outlines of the folds may be reconstructed with the assurance of reasonable accuracy. But among the Colorado

Rockies the deformed sedimentary strata, to which one must look for the record of the folding, have been completely removed from large areas by the great denudation which the region has suffered. In those areas the pre-Cambrian granites and gneisses now constitute the surface formation. Over such crystalline areas folds can be projected only diagrammatically and a large element of error, or at least of uncertainty, is necessarily involved. In Middle Park, sediments of Uinta age, deposited after the folded ranges had been greatly eroded, now hide from view several miles of the deformed terranes. Tertiary basaltic lava flows also effectively

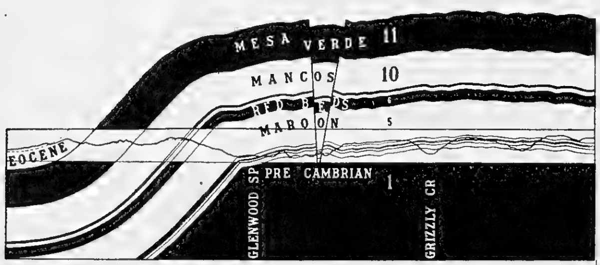

FIG. 11.—Glenwood Springs sheet (No. 13) and Grand Hogback sheet (No. 14), which covers the westernmost five miles of the section. Formations: (1) pre-Cambrian granite; (2) Sawatch; (3) Yule limestone and Parting quartzite; (4) Leadville limestone; (5) Weber and Maroon; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde. Upturned Eocene beds (mostly Wasatch) on west margin of Grand Hogback sheet.

conceal the folded structures at a number of places in the section. Of these difficulties the basaltic lava covers are the least formidable, owing to their lesser area and more patchy pattern, which makes it possible in many places to infer the concealed structure from nearby outcrops of the folded beds. But the combination of these adverse conditions makes the Colorado Rocky Mountain section far less satisfactory than that of the Appalachians.

The entire cross-section of 135 miles was plotted on a scale of $\frac{1}{31680}$ on sheets of co-ordinate paper 20 inches in length, thus making each sheet cover 10 miles of section. Thirteen and a half sheets thus compose the plotted section. But in computing the amount of crustal shortening and the thickness of deformed shell, the most easterly 3 miles of the section were excluded from con-

sideration because they are truly a part of the plains and do not properly belong to the folded belt. The truly folded section is thus reduced to 132 miles in length (Figs. 5–11).

THE SHORTENING OF THE CRUST

Folding of strata under horizontal compressive stress is necessarily accompanied by a horizontal shortening of the deformed portion of the earth shell. The compressed mass is shortened in at least one of its horizontal dimensions, while it relieves itself by bulging upward in the direction of least resistance. The first objective in our problem is to determine the amount of horizontal crustal shortening which the Rocky Mountain region underwent while writhing in the throes of diastrophic revolution. The original length of the Lyons–Grand River section before folding may be determined with some approximation by measuring the total length of a selected layer through all the sinuous bends and wrinkles which are recorded on the plotted cross-section. A small corrective factor for the compacting of materials under the compression is to be introduced. The present horizontal length to which the section has been compressed is simply the map distance between the two ends of the section measured along the slight curve which was chosen so that the section shall cross the folds at right angles as explained on page 227. The difference between the length of the strata followed through all the folds and faults as reconstructed and the present map distance of the same section is the approximate shortening which the earth shell has suffered in being crumpled into mountains.

For measuring the length of the wrinkled strata all members of a thick series of sediments are not likely to be of equal value. In folds of the type technically known as similar, the individual beds have all been folded with the same curvature.[1] But in parallel folds, where the bedding surfaces are mutually parallel, the curvature of no two beds is exactly the same, and this difference in curvature implies the dying out of the folds in one direction or the other from a given bed. Hence an element of error is likely to be introduced in the hypothetical projection of younger beds over eroded

[1] C. K. Leith, *Structural Geology* (1913), pp. 106–7.

anticlines, or of older beds in the troughs of deep synclines. This error increases with the vertical distance from the observed stratum. It is clear therefore that cross-section measurements designed to give the crustal shortening should be made on stratigraphic horizons as near as practicable to those on which the field observations were actually made. The error of mechanical projection is then less serious.

Competent and incompetent beds also behave differently in folding. Various secondary adjustments between the different beds are, in many cases, accomplished by minor contortions and subordinate movements within the readily yielding incompetent layers, which, by accommodating themselves in buffer-like fashion to the major movements, facilitate the folding. The strong, competent layers, less subject to local irregularities, are likely to reveal truer estimates of the shortening of a region as a whole.

The ideal horizon for measurement should therefore have the following qualities: It should be stratigraphically near the beds on which the observations were actually made; it should be the top or bottom of a rather thin formation so as to limit variability; the formation should be resistant and hence predisposed to outcrop sharply in the field; it should be readily distinguished from other formations; and it should be so located in the column as to come to the surface at many places in the section. Such a formation in the Colorado Rockies is the Dakota sandstone. It is one of the most persistent and conspicuous of the formations, and it occupies the desired mean position in the stratigraphic column. The base of the Dakota sandstone was therefore adopted as the line to be measured in these studies.

On the cross-section sheets the base of the Dakota was followed through all the recorded folds and crenulations with a thin, flexible copper wire, which was bent so as to conform to every change of curvature. The wire was then straightened and compared with the scale for measurement. The difference between the length of the base of the Dakota, as thus measured along all the sinuosities of the section, and the present horizontal length of the section gives the amount of crustal shortening. Measuring each of the fourteen sheets separately gave the following results:

		Miles
No. 1.	Lyons sheet (westernmost 7 miles)	
	Length following base of Dakota sandstone	7.80
	Present horizontal length	7.00
	Shortening	.80
No. 2.	St. Vrain sheet	
	Length following base of Dakota sandstone	10.91
	Present horizontal length	10.00
	Shortening	.91
No. 3.	Allen's Park sheet	
	Length following base of Dakota sandstone	10.805
	Present horizontal length	10.00
	Shortening	.805
No. 4.	Continental Divide sheet	
	Length following base of Dakota sandstone	10.89
	Present horizontal length	10.00
	Shortening	.89
No. 5.	Granby sheet	
	Length following base of Dakota sandstone	11.085
	Present horizontal length	10.00
	Shortening	1.085
No. 6.	Sulphur Springs sheet	
	Length following base of Dakota sandstone	10.65
	Present horizontal length	10.00
	Shortening	.65
No. 7.	Troublesome sheet	
	Length following base of Dakota sandstone	10.45
	Present horizontal length	10.00
	Shortening	.45
No. 8.	Gore Range sheet	
	Length following base of Dakota sandstone	10.275
	Present horizontal length	10.00
	Shortening	.275
No. 9.	State Bridge sheet	
	Length following base of Dakota sandstone	10.635
	Present horizontal length	10.00
	Shortening	.635

		Miles
No. 10.	Castle Peak sheet	
	Length following base of Dakota sandstone	10.20
	Present horizontal length	10.00
	Shortening	.20
No. 11.	Gypsum sheet	
	Length following base of Dakota sandstone	10.235
	Present horizontal length	10.00
	Shortening	.235
No. 12.	Dotsero sheet	
	Length following base of Dakota sandstone	10.29
	Present horizontal length	10.00
	Shortening	.29
No. 13.	Glenwood Springs sheet	
	Length following base of Dakota sandstone	10.265
	Present horizontal length	10.00
	Shortening	.256
No. 14.	Grand Hogback sheet	
	Length following base of Dakota sandstone	6.20
	Present horizontal length	5.00
	Shortening	1.20
Summation:	Entire Lyons–Glenwood Springs section	
	Total original length (base of Dakota sandstone)	140.69
	Present horizontal length	132.00
	Total shortening	8.69

According to these measurements, the lateral thrusting which produced the Colorado Rockies compressed 140.69 miles of country into 132 miles, thus bringing two points on opposite sides of the folded belt 8 miles closer together than they were before the folding commenced. A crustal shortening of 8 miles distributed throughout a belt of originally 140 miles in breadth does not indicate very intense horizontal thrusting. The horizontal compression was much less than in the Pennsylvania Appalachians west of Harrisburg, where 81 miles were compressed into 66 miles, thus involving a shortening of 15 miles in this much narrower belt.[1] The

[1] *Jour. Geol.*, XVIII (1910), 235.

Colorado Rockies are therefore mountains in which the horizontally operating forces have achieved only moderate results. Farther north in Montana and Alberta, however, the great overthrust faults on the Rocky Mountain front imply that the horizontal thrusting has there been much greater.

THE ELEVATION OF THE FOLDED TRACT

When a region is folded by compressive stress, the horizontal shortening is compensated by vertical bulging, except in so far as there be an actual reduction in the volume of the material deformed. According to our fundamental postulate, if the amount of crustal shortening and the amount of the resulting vertical bulge be known, the thickness of the folded shell may be calculated. It is next in order to determine, if possible, the amount of vertical uplift which has resulted from the folding.

The first requisite for the determination of the amount of upswelling is a datum-plane above which the heights of the folds are to be measured. This datum-plane should coincide in position with the original surface of the region just before the folding commenced. The chief difficulty is to locate a datum-plane available today which will correspond in position to the original surface before folding. Mountains ideally built for such a study should be folded from a plain which was just at sea-level. A minimum of epeirogenic movement should accompany the orogenic disturbance. Then without the entrance of any other diastrophic changes to add complications, erosion should again reduce the folded tract completely to base level. This base level should correspond as closely as possible to the sea-level from which the mountains originally rose. This base level would then constitute the proper datum-plane above which to measure the heights of the folds.

The history of the Colorado region has been such as to render it rather well suited to a treatment of this sort. The closing stages of the Cretaceous period in Colorado witnessed a transition from the conditions of marine sedimentation to those of terrestrial deposition. Among the last beds laid down before the inauguration of the Laramide folding were vegetable accumulations which have since become coal. They were presumably formed in marshes

which were very close to sea-level. The Colorado sea-level at the close of the Cretaceous thus becomes the critical level. It was a plain approximately at sea-level which was arched and wrinkled into the Rocky Mountains by the diastrophic throes of the dying Mesozoic. Erosion by the rapid streams which sprang into being assailed the uplifted ranges and in time reduced them to the condition of a peneplain. But was, or was not, the level of this peneplain approximately the same as the level of the plain which earlier was folded into the mountains, and whose position today is such an important factor in our problem?

If it were known that the peneplain now visible in various portions of the Front Range had been developed at an elevation not greatly above sea-level, and that no changes of level had occurred in the interim between the period of folding and the development of this peneplain, then the latter could be accepted with confidence as the datum-plane, and it would be proper to measure the height of the projected folds above the present height of the peneplain. This of course presupposes that the orogenic folding movements were accompanied by little epeirogenic uplift. If, however, there was general regional uplift along with the folding this can be treated as subsequently indicated. But there were, in all probability, some changes of level during this very considerable period of time between the folding and the peneplain. A rise of the sea consequent upon the transfer of sediment from the uplifted lands to the ocean floor might confidently be expected. But at most this would amount only to a few hundred feet.[1] Furthermore it is to be noted that such a rise of the sea-level is in the nature of a return to the late Cretaceous conditions of widely transgressive seas, and hence toward the conditions and level from which the Rockies arose.

Far more to be feared are possible uplifts due to vertical forces operating independently of folding movements. There are two possibilities: A general regional uplift might have affected the entire area more or less uniformly; or the change in level might have been confined to local upbowings, either within

[1] R. D. George has estimated that the cutting away of the present continents and the deposition of the material in the ocean basins, would raise the sea-level about 650 feet. Chamberlin and Salisbury, *Geology*, I, 545.

the granite areas of the main ranges where it would readily escape notice, or within the areas of folded sedimentaries, portions of which might have been raised without materially increasing the intensity of the folding. But on the other hand renewed horizontal thrusting which merely carried further the folding process would cause no harm provided the thickness of the folded shell were the same as in the previous episode of folding. If the thickness were different, however, such later deformation would add a complicating factor. The folded Eocene volcanics at Windy Gap on the Grand River show that the folding cannot all be assigned to a single period, and this later folding may have been fully as intense in the region in question as the earlier Laramide diastrophism.

Although these are admittedly embarrassing factors which may have operated to some extent and which, if they did, lessen the accuracy of the final results, still it is believed that quantitatively they probably were not of sufficient magnitude to alter the general purport of the results. When it is noted that the average height of the folded tract throughout the entire section, according to measurements, is slightly over 13,000 feet above the datum-plane, it is apparent that a concealed, or unrecognized, uplift of 1,000 feet, or even 2,000 feet, will not change the order of magnitude or general significance of the results. The former would amount to but 7.7 per cent of the total; the latter to 15.4 per cent of the total. It is also frankly to be recognized that the method of projecting folds involves at best some error, and that when granite areas are included in the section the possible error becomes just so much greater. Such errors are inevitable owing to the limitations which the section imposes, and in the Colorado Rocky Mountain case they are considerable. Hence it is believed that refinements of method such as the introduction of corrective factors for the uplifting of the folded region during the interval between the folding and the peneplain stage, or for changes in the sea-level, or for the possible spreading and settling of the high standing mountainous masses, or for other changes, cease to be very vital in this case, though thoroughness in analysis requires their recognition. In any case they would be likely to offset one another more or less. The measure of inevitable error inherent in the section itself is so

considerable that it is scarcely worth while to attempt to evaluate these subordinate factors.

Recognizing the limitations of the method, but believing that the probable errors from these complicating factors are not great enough quantitatively to affect seriously the general conclusions, and that in any case they are probably less than the errors which will always stand in the way of a dynamic study of these ranges, owing to scarcity of data upon the granite areas, this investigation will proceed on the hypothesis that the peneplain level today represents with fair approximation the original level from which the folds arose. A hypothetical picture of this situation might be as follows: The folding of the Rockies was accompanied in all probability by some general uplift of the continent as a whole. Suppose that this uplift brought the Great Plains belt adjoining the Rockies to an elevation of 2,000 feet above the sea. Let us assume that the base-leveling process in developing the peneplain caused a rise of the sea to the extent of 500 feet. Then the peneplain, in order to constitute the correct datum-plane, should have been formed at an elevation of 1,500 feet above sea-level. Whether this imperfectly reduced Colorado peneplain, featured by many large monadnocks and nearly a thousand miles by the existent drainage routes from either the Gulf of Mexico or the Pacific Ocean, may reasonably have developed at this elevation is left to the reader to judge.

The average height of the reconstructed folded surface above this natural datum-plane was found to be as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	1.51
No. 2. St. Vrain sheet	3.13
No. 3. Allen's Park sheet	3.90
No. 4. Continental Divide sheet	4.03
No. 5. Granby sheet	2.18
No. 6. Sulphur Springs sheet	1.68
No. 7. Troublesome sheet	2.42
No. 8. Gore Range sheet	2.40
No. 9. State Bridge sheet	2.24
No. 10. Castle Peak Sheet	1.62
No. 11. Gypsum sheet	1.98
No. 12. Dotsero sheet	2.54
No. 13. Glenwood Springs sheet	2.83
No. 14. Grand Hogback sheet	0.43

These figures should therefore represent, subject to the above-mentioned qualifications, the degree of uplifting which has resulted from the folding process.

It will be seen that in the matter of uplift the Grand Hogback sheet falls far short of all the others and appears to be in a class by itself. An inspection of the Grand Hogback section reveals the fact that, while the eastern half of the sheet shows moderate uplift, the western half, on the contrary, indicates subsidence, for the upper surface of the Cretaceous there dips more than 5,000 feet below the datum-plane. Only Tertiary rocks are exposed at the surface in the western portion, and in fact the geological map of Colorado shows that these Tertiary rocks continue to the southwest without interruption for fully 50 miles more—even to within 20 miles of Grand Junction. This area west of the Grand Hogback constitutes the southeast portion of the extensive Uinta Basin, which is a structural basin filled with thick Eocene deposits. Throughout this basin of heavy Eocene sedimentation the upper surface of the Cretaceous has been depressed below our datum-plane.

The Grand Hogback is a sharp ridge of upturned resistant strata, which marks the location of a sharp monoclinal flexure between the uplifted Rocky Mountain region on the east and the downwarped Uinta Basin to the west. A study of the Grand Hogback cross-section sheet raises the question whether subsidence of this basin of Eocene sedimentation may not have been as important in developing the Grand Hogback monoclinal flexure, as upwarping on the Rocky Mountain side. But whether subsidence or uplift has been the more effective in bending the strata, the earlier Eocene beds in any case exhibit essentially as much folding as the underlying Cretaceous, indicating that the flexing for the most part has come after the Laramide disturbance. Later studies may show whether or not this bending was synchronous with the episode of folding which affected the Middle Park beds near Windy Gap. Because the extent of the subsidence suffered by the Uinta basin interferes with any reliable determination of uplifting on its borders, the Grand Hogback sheet will not be included in the section used for estimating the thickness of the folded Rocky Mountain

shell. The measured section will thus end with the western edge of the Glenwood Springs sheet, $1\frac{1}{4}$ miles southwest of Glenwood Springs.

Since the country was corrugated into the lofty folds portrayed by the reconstructed cross-section, the high-standing areas have been subject to some relaxational movement. Portions of the area have settled by the process of normal faulting. It is to be noted that all the faults shown in the cross-section are located on the limbs of anticlines or in the plateau-like region between State Bridge and Glenwood Springs. The faults appear to shun the synclinal troughs. This would imply a spreading of the anticlinal arches accompanied by downslipping on the sloping flanks. That more of these normal faults are located on the western limbs of anticlines than on the eastern may have been a chance matter of local conditions and so of little import, or may possibly point toward a westward creep in the relaxational process. There are several theoretical reasons why the latter might be looked for, but the evidence is so meager as to merely raise the query. Since the settling along these faults took place presumably after the folds had attained their growth, the foregoing estimates of the height of the folded tract have been made on the basis of the original folds.

THE THICKNESS OF THE FOLDED SHELL

Having estimated the crustal shortening and the vertical bulging which have arisen from the folding, the depth of the folded zone is to be calculated. According to our formula, the product of the present horizontal length of the folded section times the vertical uplift equals the product of the shortening times the depth of the folded shell (Fig. 12). This is true except in so far as there has been an actual change in volume due to the compacting of materials under the comprehensive stresses. As discussed in a previous paper,[1] the amount of shortening due to the mashing of the strata and the compacting of materials during folding is relatively small in comparison to that resulting from corrugation—in all probability not more than 5 per cent. Furthermore, the shortening due to the compacting of the rocks is more or less offset by subsequent elongation of the strata arising from jointing, from the opening of fissures, and the penetration of igneous intrusions.

[1] *Jour. Geol.*, XVIII (1910), 236–37.

But as any corrections for these qualifying factors on the basis of present information would be essentially arbitrary, they will be passed over for the present. Corrections to cover them can, however, be introduced at any subsequent time if the necessary information should become available, or if it should be felt that these factors are of sufficient quantitative importance to justify their further consideration.

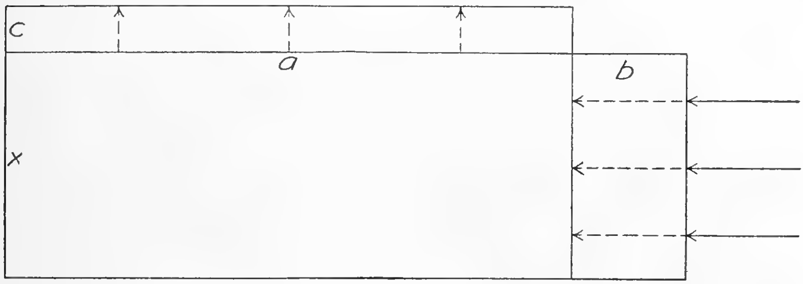

FIG. 12.—Diagram to illustrate the method of calculating the depth of a folded block.

a = the present horizontal length of the section
b = the shortening caused by the folding
c = the upbowing resulting from the folding
x = the depth of the deformed block

Then $(a+b)x = a(x+c)$

$$ax+bx=ax+ac$$

$$x=\frac{ac}{b}$$

Using the method above outlined, the thickness of folded shell was calculated separately for each ten-mile sheet of the Lyons–Grand River section. The results were as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	13
No. 2. St. Vrain sheet	34
No. 3. Allen's Park sheet	48
No. 4. Continental Divide sheet	45
No. 5. Granby sheet	20
No. 6. Sulphur Springs sheet	26
No. 7. Troublesome sheet	54
No. 8. Gore Range sheet	87
No. 9. State Bridge sheet	35
No. 10. Castle Peak sheet	81
No. 11. Gypsum sheet	84
No. 12. Dotsero sheet	88
No. 13. Glenwood Springs sheet	107

The results are presented diagrammatically in Fig. 13, in which each section has been represented as though it were an isolated rectangular block, no attempt being made to accommodate these blocks to one another as was done undoubtedly in the real case.

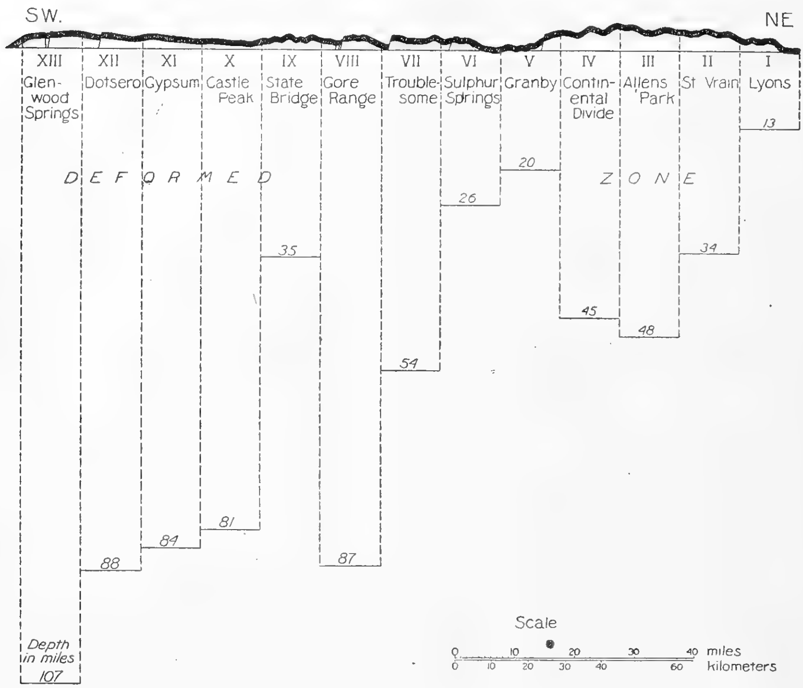

FIG. 13.—Diagrammatic cross-section of the deformed zone for this portion of the Colorado Rockies. The thirteen separate blocks are numbered in order from northeast to southwest. The heavy black line gives a restoration of the Laramie and Mesa Verde formations and thus represents the original folded surface. The depth in miles is given at the bottom of each block. No attempt is made to bound the deformed zone by a curved lower surface, as was presumably the actual case in the field.

Curved boundary lines would certainly conform more closely to nature, but nothing more than the strictly diagrammatic block-outline is ventured here.

Fig. 13 appears to show that beneath the two principal granite ranges, which today mark the lines of greatest upfolding, the disturbed zone reached deeper levels than on the immediate

flanks of the upfolded belts. The granite mountain belts are more deeply rooted than the less uplifted strips adjacent. They constitute the true Rocky Mountains of this latitude.

According to the testimony of the Lyons sheet the folded shell of the Front Range thins rapidly as it approaches the Great Plains. This repeats in type, though less strikingly, the rise of the boundary shearing plane on the western border of the Appalachian Mountains near Tyrone, Pennsylvania.[1] Neither the Lyons section nor the Tyrone section developed an actual fracture, though they suggest an approach to it. But on the western border of the Appalachians farther south the boundary shearing plane has actually emerged from the depths as a strong thrust fault which separates the disturbed mountainous belt on the east from the region of horizontal strata on the west. This is especially conspicuous in Tennessee. In close analogy to this, in Montana and Alberta, the Rockies are separated from the Great Plains by an overthrust fault, or faults, of great displacement. These instances pointedly suggest the generalization that bordering thrust faults, particularly on the inland margin of a strongly deformed mountain belt away from the assumed active oceanic segment, are a common, and if so significant, phenomenon, especially as they accord with the theory of mechanics. With greater intensity of thrusting and the appropriate rock materials, the great upfold in the foothill belt of the Colorado Rockies would presumably have passed into a bordering thrust fault.[2] Such a bordering thrust fault appears to have developed on the east flank of the Wet Mountains, where that range continues the Rocky Front *en échelon*, south of the Arkansas River.[3] The pre-Cambrian granite has been thrust eastward over the Cretaceous strata of the plains and lower foothills, and also in one place over a conglomerate which has been classed tentatively as Arapahoe.

The westernmost four divisions of the plotted section, representing the region of but slightly disturbed strata between State

[1] *Jour. Geol.*, XVIII (1910), 245, Fig. 6.

[2] Some local fracturing did develop at Boulder and at Golden. See Ziegler, *Jour. Geol.*, XXV (1917), 728–40.

[3] C. W. Washburne, "The Canon City Coal Field, Colorado," *U.S. Geol. Surv., Bull. 381* (1910), p. 342 and Pl. XVIII.

Bridge and the Grand Hogback, constitute in reality a plateau region rather than a folded mountain area. This strip is to be considered the southeastern extension of what has been called the White River plateau. In fact the deformation in the westernmost forty miles of the chosen section was so slight that this strip was not originally included in the folded mountain section measured in 1915. It was added in 1916. Fig. 13 indicates that beneath this region of plateau-like uplift the lateral thrusting movement has been distributed through a thick zone which has been deformed only slightly.

To interpret Fig. 13 the deforming movement pictured as the result of thrusting from the west was distributed at first through a thick shell in the plateau region, but in this thick zone it reached only a low degree of intensity. The region was in consequence but feebly wrinkled. But in the region next east, where the Grand River today turns abruptly northwestward near State Bridge, the activity was concentrated in a thinner movable zone which was far more sharply folded. This marks the western flank of the folded belt which culminated in the Gore or Park Range. Next east of this, less folding in the middle of the Gore Range indicates greater depth of shell there, followed by thinning again on the eastern flank of the Gore Range. The disturbed mass became thinner again in the Middle Park region, where the uplifting was relatively less, and then it deepened rapidly beneath the Front Range, where the uplift was greater, again thinning out rapidly to the edge of the Great Plains, which border the folded belt on the east. In this way the Front Range repeated the wedge-shaped block of the Park Range.

These results are based on the assumption that the shortening has remained the same throughout the full depth of each deformed block. If the shortening, in reality, increases with depth these figures are overestimates of the thickness of the folded shell. But on the other hand, if it be true that there was less folding and less shortening in the deeper portions of these blocks, these figures are underestimates of the depths to which the folding extended. Of the two alternatives the latter seems the more probable. With increasing depth below the surface, the resistance of the rocks to

deformation steadily increases, thus necessitating greater and greater stress differences in order to cause folding. Unless the stress differences increase as rapidly as does the resistance with increasing depth below the surface, folding, instead of becoming easier in the deeper levels as the time-honored doctrines have taught, becomes more and more difficult and hence less effective.[1] Daly has called attention to the fact that in the Selkirk Range of British Columbia the Shuswap terrane of presumable Archean age has escaped much of the folding which so powerfully affected the younger rock systems. The basement rocks show comparatively slight deformation, from which Daly concluded that "the earth shell engaged in the post-Shuswap orogeny was only a few miles, perhaps 6 or 8 miles, in depth. Over the Shuswap terrane this shell was thrust and crumpled."[2]

Beneath the surface the sharpness of folding probably at first increases down to a level of greatest folding, below which it again diminishes. With increasing depth below the level of sharpest folding, the folds of the wrinkled shell may either die out gradually or the adjustment may be accomplished by shearing between the upper, more movable portion and the lower, less movable portion. Fig. 13 is based on the assumption of undiminished intensity of folding throughout the full depth of each deformed block, and hence calls for adjustment by shearing below. In the actual case the adjustment was probably accomplished, not by shearing alone, but by some combination of the two processes. But at present the relative importance of the two cannot be decided, except upon arbitrary assumptions. Too much weight must, therefore, not be given to the precise figures for the depth of the various blocks.

Estimates of the depth of deformed shell by this method are subject to modification for such uplifts as were not occasioned by the horizontal compression. In this section of the Colorado Rockies it is quite possible that upbowing has recurred along the

[1] F. D. Adams and J. A. Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV (1917), 597–637.

[2] Reginald A. Daly, "A Geological Reconnaissance between Golden and Kamloops, B.C., along the Canadian Pacific Railway," *Geol. Survey of Canada, Mem. 68* (1915), pp. 53–55.

old lines of yielding during the critical interval between the folding of the mountains and the establishment of the peneplain, and any such vertical movement whose occurrence and extent have not been detected and duly covered by a correction, would reduce the accuracy of the calculated results. But on the other hand, any uplifts subsequent to the development of the peneplain do not in any way enter into the problem, for the adopted method of treatment eliminates their influence. The testimony of folded mountain ranges in general is to the effect that later episodes of yielding commonly follow along the lines of earlier folding, doubtless because they have become the lines of least resistance. These later episodes of diastrophism may obviously be either further folding under compressive stress or uplifts with but little folding. The effect of the latter possibility in the case under discussion would be to increase the height of the folded section, without correspondingly adding to the measured shortening, and thus make the calculated depths of the Gore Range block and Front Range block too great. The other alternative of further folding along the old lines is less serious, for, as has been stated before, the outcome of the computations will be the same whether the folding all took place at one time or at different times, provided the same thickness of shell was affected each time. If two or more episodes of folding deformed different thicknesses of shell, the computed depth resulting from the adopted method of treatment would be in the nature of an average. In this connection it is of significance to note the statement of Hills that the post-Bridger folding was essentially a continuation of the post-Laramie folding, for the second movement began where the first terminated, and if the post-Laramie movement had been further continued the resulting structure might ultimately have been the same.[1]

In contrast to uplifting, any subsidence of intermontane basins of deposition, or local downwarping, during the critical interval between the mountain folding and the development of the peneplain would tend to offset the bulging effect of the folding process, and thus lead to a too low estimate of the height of the folded tract. This in turn would result in giving an underestimate of

[1] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), 419.

the depth of the folded block. In certain portions of the Granby, Sulphur Springs, and Troublesome areas, beds of Uinta age occupy several basins below the peneplain level. The position of these beds strongly suggests a sinking of these basins under the accumulation of early Tertiary times. Though the extent of the settling probably was not great, still it may have been sufficient to cause the calculations to assign a somewhat too meager depth to the rather shallow Granby and Sulphur Springs blocks.

In the foregoing computations only the crustal shortening at right angles to the trend of the ranges has been considered. But folds are properly considered in three dimensions, and some longitudinal warping and pitching of the folds is to be expected. Longitudinal warping would involve crustal shortening in a direction parallel to the trend of the range and at right angles to the shortening above considered. The folds measured in the Lyons–Grand River section exhibit pitching in some places, but this did not appear sufficiently pronounced to justify the extra field work necessary to measure the northwest-southeast warping for the different sections. The warping at right angles to the main folding was most apparent in the State Bridge and Glenwood Springs sheets. This minor warping, like the major folding, causes upswelling of the folded tract. Hence in practice the effect of ignoring the minor warping in the direction of the ranges is to assign all the observed upswelling to the work of the major folding and thus obtain an overestimate of the depth of the folded zone.

There are therefore certain subsidiary considerations, such as uncorrected uplifts subsequent to the folding, and the neglect of upswelling from longitudinal warping whose influence is to cause overestimates of the depth of folded shell. But over against these is the uncorrected sinking of certain areas of Eocene sedimentation, and the assumption of uniform shortening throughout the full thickness of each deformed block, whose probable influence is to cause underestimates of the depth. In all probability each of these is the source of some error. How nearly they offset each other and so cancel out of the equation cannot be told at present. But they probably do not greatly modify the general order of magnitude of the calculated results.

GENERAL DISCUSSION AND CONCLUSIONS

These studies would seem to show that the Colorado Rockies differ in several notable respects from the folded Appalachians of Pennsylvania.

1. They have suffered, in the first place, much less horizontal compression. From the Great Plains to the Uinta Basin, 140 miles of country were compressed into 132 miles, thus involving a shortening of only 8 miles, while west of Harrisburg alone 81 miles of strata were squeezed into 66 miles of present Appalachians, which means a shortening of 15 miles in this much narrower belt. This does not include the folding in the metamorphic belt east of Harrisburg.

2. A much thicker shell seems to have been involved in the Rocky Mountain diastrophism than was actively deformed in the Appalachian folding. The apex of the Pennsylvania Appalachian wedge was but 32 miles below the surface, while the roots of the Gore Range reached a depth of 87 miles and the plateau tract near Glenwood Springs had a depth of 107 miles.

3. Vertical lifting and plateau-forming movements have been more pronounced in the Rockies than in the Appalachians. This is indicated both by the outcome of this analysis, and also by the present high altitude of the Colorado Front Range peneplain, though the elevation of the latter, to be sure, came long after the principal folding, which is the basis of this investigation.

4. The formation of the Colorado Rockies was accompanied by much more vulcanism than the formation of the Appalachians.

These conclusions lead naturally onward to certain additional deductions and further applications. These specific results confirm the principle that there is an inherent relation between thickness of shell actively involved and intensity of deformation. This justifies the conclusion that mountain ranges displaying intense folding, thrust faulting, and dynamic metamorphism resulting from extreme horizontal compression are associated with a thin, shallow shell. This thin, movable shell, which has been greatly folded and faulted, shears upon the less yielding base beneath it. Ranges of this sort are the Appalachians and presumably the Jura, Alps, Scottish Highlands, Scandinavian chain, and others of great short-

ening and intense horizontal thrusting. If the active crumpling in a range like the Alps were not confined to a very thin shell the resulting vertical bulge would be stupendous.

Those ranges in which a much thicker shell has yielded to the stresses are characterized by open, gentle folding, only moderate shortening, but more pronounced vertical lifting. The Colorado Rockies belong to this group. Moderate folding distributed through the thicker zone accomplishes the same amount of vertical bulging as greater shortening of a thinner zone. Shearing along a few well-defined planes may well be a less important means of adjustment beneath the thicker deformed zone than beneath the thinner one. Adjustment in the thicker zone is probably due to gradual accommodation by the slow dying out of folds below, with perhaps more or less local, distributive shearing. Upward yielding in the direction of least resistance being relatively more conspicuous than horizontal movement when a thick shell is deformed, this type of mountain building crowds closely on the borders of the plateau-forming type of diastrophism. The western portion of the Lyons–Grand River section, from State Bridge to the Grand Hogback, where the disturbed zone had a thickness rising from 81 to 107 miles, portrays what was essentially a plateau uplift, and suggests the actual merging of this mountain type into the plateau type.

An incidental feature of some significance is the bordering thrust fault observed in several instances on the inland margin of a strongly deformed mountain belt farthest removed from the oceanic segment from which the thrusting presumably has come.

Since the Laramide disturbance the Colorado Rocky Mountain region has been the scene of much vulcanism. The products of this, in places, have obscured the folded strata beneath, and thus have added materially to the difficulty of making an accurate cross-section of the mountainous belt. In general, Tertiary vulcanism has been a prevailing phenomenon throughout the Rockies from Montana to New Mexico. In the region of the present Appalachian Mountains, on the other hand, there has been very little vulcanism. There were the Upper Triassic lavas of the Newark series, to be sure, but they were east of the present mountains and,

breaking out long after the Appalachian folding, they appear to be genetically related to faulting nearer the coast in a diastrophic movement which occurred toward the close of the Triassic. Lavas and tuffs caused no trouble in measuring the Pennsylvania mountainous section.

In view of the fact that the Pennsylvania Appalachians, which show less volcanic activity, have resulted from the crumpling of a comparatively thin surface shell, while the Colorado Rockies, with more extensive vulcanism, involved a thicker shell, it is suggested that there probably is a genetic relation between the depth to which the roots of a mountain range extend and the amount of vulcanism associated with it. It seems very rational a priori that if the zone disturbed in the formation of a folded range does not extend far below the surface, it would not be likely to lead to the generation of magmas nor greatly facilitate their escape if already present in the undisturbed depths below, even though the folded zone itself may be intensely deformed and shear strongly over the underlying base. But if, on the other hand, the disturbed zone reaches down to considerably greater depths, even though the deformation itself be not so intense, it may readily afford better opportunities for the generation or the rise of magma to the surface. At many points the difference in depth of disturbance may be sufficient to decide between a rise of magma and no upward movement of the magma, or by operating through relief of pressure, perhaps decide between potential magma and actual magma.

On theoretical grounds the thin-shell mountains should be accompanied in their growth by relatively little vulcanism, while the growth of thick-shell mountains should be attended by relatively greater outpourings of lava. Looking over the mountain systems of the globe one might select, as some of the conspicuous illustrations of sharp folding, great thrust faulting, and much crustal shortening, the Alps, the Scandinavian chain, the Scottish Highlands, the Backbone Range of Brazil, and perhaps the Rocky Mountains of Alberta. These would seem to be mountains of the thin-shell type as nearly as can be judged without actual measurements upon them. In each of these cases it will be observed that only moderate igneous activity was associated with the mountain

building. This seems perhaps the more remarkable when it is considered that any great disturbance of the outer portion of the earth is likely to stimulate outward movements of liquid magmas, and in some cases through relief of pressure actually to cause liquefaction and the development of magmas.

As representatives of the thicker-shell type of mountains in which vertical movements are more pronounced, and horizontal thrusting and shortening less conspicuous, one might select in addition to the Colorado Rockies, the Cascades on the Pacific Coast,[1] the great chains of Andes, particularly the Western Andes, and the Abyssinian Mountains. The extravasation of vast floods of lava marked the growth of these ranges. In the light of this inquiry, it may be inferred that these mountains had deeper roots than the more sharply folded ranges, and that this greater depth of disturbance was an important factor in causing the greater igneous outbursts.

In final summation it may be remarked that within Colorado the Rocky Mountain system is characterized by open, gentle folding, moderate crustal shortening affecting a zone several scores of miles in depth in its deeper portions, by strong uplifting, and by the extrusion of much lava. Extending the range of view, it is to be noted that this dominantly vertical diastrophism with its ample outpourings of lava is typical of much of the western United States. On the other hand, in northwesternmost Montana and throughout Alberta, the ranges of the Rocky Mountain system exhibit low angle thrust faulting on a grand scale, greater crustal shortening which presumably has affected a thinner surface shell, and has been accompanied by less volcanic activity. It thus appears that a single mountain system of great length may develop both types of deformation in different portions of its extent.

[1] See Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *U. S. Geol. Surv., Prof. Paper 19* (1903), pp. 95–97.

NOTES ON PRINCIPLES OF OIL ACCUMULATION[1]

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Petroleum deposits of commercial importance occur in sedimentary rocks. The great majority of such deposits in the mid-continent field are found in sands or in thin-bedded porous limestones with intervening shales. These shales are generally dark colored, often black, and carry bands of highly bituminous material. Paying amounts of oil have not been found in very thick sandstones or limestones without notable shale "breaks,"[2] or without being closely associated with shale horizons. Even the Bartlesville, the thickest pay sand of the region, shows many black shale partings when the cuttings of each screw are examined carefully.

The examination of a number of such cuttings in the proximity of many different oil sands throughout the mid-continent field reveals the fact that black bituminous shales are invariably present.[3] These beds are often described by the drillers as coal, asphalt, or black lime, according to the hardness and appearance of the material. The shales are typical oil shales, quite similar in character to those of Colorado and Utah. The bituminous material occurs in solid form as none of the ordinary solvents show coloration after solution tests. Upon distillation, such shales have given off petroleum-hydrocarbons. The sands are entirely barren of such compounds.

Before concentrations of petroleum can take place, it is necessary that this solid organic gum called kerogen be changed so that liquid hydrocarbons are formed. Such a change has com-

[1] Published through courtesy of the Empire Gas and Fuel Company.

[2] Drillers are accustomed to speak of thin changes in a thick formation as "breaks."

[3] In cuttings examined to date the one exception to this statement is the Hoy (1,100 feet) sand of the Garber, Oklahoma, field.

monly been made in the laboratory by heating. However, the majority of oil deposits are located in the upper 3,000 feet of sediment, and evidence that the necessary distillation temperature of 450° F. has ever been reached at such places is quite lacking. Oil-field waters of this region are seldom above 100° F. in temperature, ranging generally from 80 to 90° F. Consequently it is difficult to explain the reduction of liquid oil from bituminous shales by heat, except possibly in very limited local areas of intense friction. Even in such cases the amount of heat is highly problematical.

The other most important factor below the surface of the earth is pressure. Pressure alone can cause no change in this material when the included water is not allowed to escape, and the shales are only compacted when the water is given free passage.

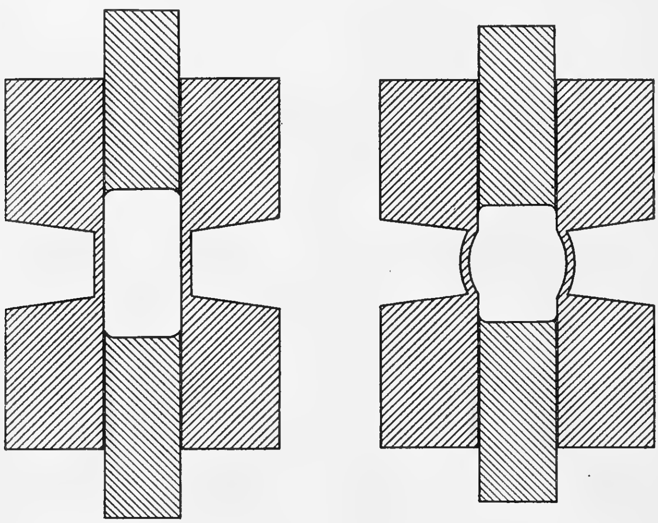
These facts led to a laboratory investigation of rock flowage upon the hypothesis that the mechanical energy or work done upon the shale by applying a force through a distance would accomplish the same results as the equivalent amount of heat energy. The experiment was carried out by Mr. E. A. Trager and the author, similar to the experiments of Adams and Bancroft.[1]

1. *Description of flowage experiment.*—Cylindrical steel bars (Fig. 1) were sawed in lengths of about 3 inches and bored into tubes having an inside diameter of 2 cm. The thickness of the walls in the center of the cylinders was reduced to 0.25 cm. Pistons of steel were turned to fit the tubes. Cylindrical pieces of an oil shale (yielding 25 gallons per ton and having a crushing strength of about 3,000 pounds per square inch) were cut into 1-inch lengths and placed in the center of the tubes, where the thickness of the walls was reduced. The pistons were then inserted on either side of the shale cylinder and pressure was applied to them in a Riehle compression machine, thus squeezing the shale and eventually bulging the tubes in the center. By so doing, the shale was made to flow. No appreciable amount of heat was was developed. Solution tests taken before the experiment gave no indication of liquid hydrocarbons, while those taken after flowage with the same shale gave strong coloration. In some cases, after the experiment small globules of oil could be seen in the shale with a hand lens. The steel tubes necessitated

[1] Adams and Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV, 597.

such a great pressure to make the bulging that tubes of brass and softer metals were tried. The results were substantially the same. Details of this work will be described in some later paper.[1]

The experiment is referred to here in order to show how liquid hydrocarbons may be formed in the shales from the solid bituminous material at ordinary temperatures and under pressures of 5,000 to 6,000 pounds, such as exist at the depth of oil-bearing horizons; and that the only places where such compounds would be formed are in areas of differential movement.



BEFORE COMPRESSION AFTER COMPRESSION

FIG. 1.—Longitudinal section through steel cylinder inclosing rock column

After the oil is once formed in the shales, it is collected in the porous zones by water. The action is one commonly called "Capillary Concentration."[2] Water, having a greater surface tension and adhesion for shale particles than oil, moves into the smaller openings of the shale, and the oil is thus forced into the larger openings of the porous water horizons. Before this can take place, the water sand or reservoir rock must come in direct

[1] Unpublished manuscript of E. A. Trager and the author.

[2] C. W. Washburne, *American Institute Mining Engineers*, 1914, p. 830.

contact with the oil-soaked shale. Oil shales are usually separated from sand or porous rock by barren shales. These overlying and underlying a water stratum would be saturated with capillary water, and it would be impossible for oil to migrate through even a very thin water shale, for reasons stated later. It then becomes necessary for breaks in the intervening shale to occur so that the water may come in direct contact with the oil-soaked horizon. Such conditions can be brought about only by faulting or jointing. A very small displacement or a slight open joint may give the water from large openings a chance to

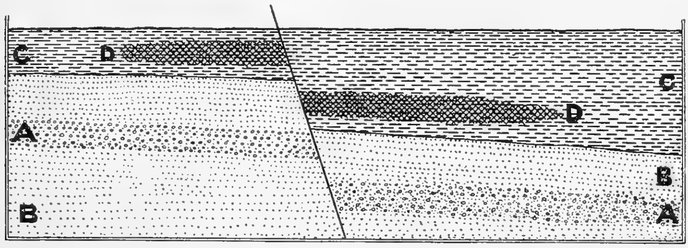


FIG. 2.—Diagram of apparatus for accumulation experiment before partition was removed, showing oil in shale marked "D."

enter the oil-soaked shale and the oil to exchange places with the water. To substantially back these statements, the following experiment is offered:

2. *Description of accumulation experiment.*—A water-soaked sand bed (*B*) two inches thick was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 2). In the center of the box a celluloid sheet partition was set at a slight angle to the vertical and effectively sealed to the sides and bottom of the box with putty. Each division of the box was then water-tight. The sand bed was built higher on one side of the partition than on the other; the beds on each side of the partition were slightly sloping in the same direction, representing a normal fault. About one inch below the top of the sand bed was a thin layer of coarser sand (*A*) running uniformly throughout. Water-soaked mud (*C*) from ground shale (passing a 200-mesh sieve) was placed above the sand. This layer was about one inch thick. Then a one-inch layer of oil-soaked mud (*D*) was built over the area adjoining the celluloid partition, but not extending to the corners of the box. The reason for not covering the entire area with oil-soaked shale was to avoid the fittings around the corners as a perfect seal is hard to accomplish in corners of such a small box. The

remainder of the box was filled with water shale. Each formation had the corresponding displacement on either side of the partition. The box was allowed to stand for twenty-four hours. No movement of the oil was noticeable after that time. The celluloid partition was then carefully pulled out so that the beds were undisturbed and the softer beds of the shale immediately closed the small opening left by the removal of the sheet. Within one hour from this time oil began to collect in the porous layer of the sand. This continued for several hours until the porous sand was nearly filled on each

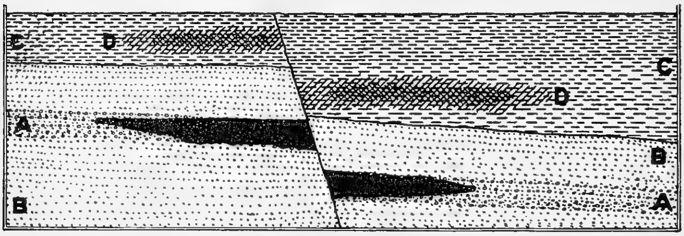


FIG. 3.—Diagram of apparatus for accumulation experiment after partition was removed, showing oil partially replaced from "D" and accumulated in "A."

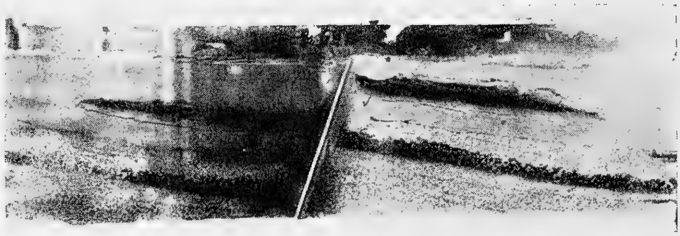


FIG. 4.—Photograph of apparatus used in Experiment 2, showing the accumulation of oil in the sand.

side of the represented fault (Fig. 3). Capillary water partially had replaced the oil in the original oil-soaked shale and had sealed the remaining oil completely in the center of the shale body. After the oil had come to an equilibrium in the sand, it did not move apparently up the dip but remained in the porous zone surrounded by water. The relative position of oil and water was stationary until the experiment was torn down two weeks later. Note photograph shown in Fig. 4.

The foregoing evidence shows that liquid petroleum in shale cannot move into the porous water horizons until the intervening

barren shales are opened by joints or the oil shale layer faulted against water strata.[1]

Capillary action is very slightly increased with the increase of pressure,[2] consequently the movements underground are not materially different from those in the laboratory. The action, however, varies with the absolute temperature of the liquids, but in the upper 5,000 feet of sediment the temperatures would not alter the actions as described.

When the oil once reaches the sand or porous zone, it adjusts itself to occupy the larger openings and remains there indefinitely unless disturbed by some outside factor.

It is impossible for oil to migrate any great distance in the oil-bearing formations of the mid-continent field. A discussion of this point is taken up in three parts: (1) difficulty of migration from the mechanical standpoint; (2) negative experimental evidence; (3) evidence of lenticular character of water zones.

The movement of oil in water-soaked sediments is almost entirely a problem of surface tension. Water, having a greater surface tension and attraction for rock surfaces than oil, moves into the smaller pores occupied by the oil and forces it into larger openings. Such movement is characteristic as long as the openings are less than 0.1 mm. Where the sand grains are unusually large (3 mm. in diameter or over) or where induced openings have been made locally in some hard formation, sorting due to specific gravity is free to take place if the unbalanced weight overcomes the friction of the movement.

Relative forces thus affecting oil movement can be figured from the size of the openings in the rocks.[3] In a shale at a depth of 1,500 feet, where openings are 0.01 micron, the capillary force

[1] It is the popular belief that faults are detrimental to oil accumulation since they afford passages for upward migration of oil, thereby allowing the oil to escape. Such may be the case occasionally where the formations stand open along the fault plane for hundreds of feet. In the oil fields of Oklahoma most faults probably never reach the surface. Shales being so predominant in the section invariably fall together along the fault plane, thus tightly sealing the majority of faults so that they are not generally conductors of oil upward.

[2] Johnston and Adams, *Jour. Geol.*, XXII, 9.

[3] *Ibid.*, p. 13.

of the water to replace the oil is about 1,400 lbs. per square inch;[1] the unbalanced force due to specific gravity is less than 0.1 lb. per inch; and frictional resistance is probably a fraction of a pound per square inch. As the openings become larger the capillary-expelling force of the water becomes less and when these have reached 0.5 mm. this force is zero. Then the unbalanced specific gravity and fractional resistance are the only forces to be accounted for. Such places are only local in the sedimentary series, and the great majority of openings in oil-bearing formations are much smaller. The force necessary to make oil migrate through a wet shale (openings 0.01 micron) for a depth of 1,500 feet is about 4,000 lbs. per square inch. This is about 1,500 lbs. per square inch greater than the combined rock and complete hydrostatic pressure. Consequently, it is utterly useless to assume migration of oil through wet shale. Even when the openings in a sandstone are as much as 0.1 mm. in diameter, the capillary resistive power is about 0.4 lb. per square inch compared with 0.1 lb. per inch, the unbalanced force due to specific gravity. The instant an oil particle (migrating in water sediments) reaches a series of openings larger than those surrounding it, it stops and remains there indefinitely, as long as these surrounding openings are less than 0.1 mm. All sandstones are irregular and a series of openings larger than 0.1 mm. is never very extensive.

3. *Experiment on migration of oil in wet sand.*—A water-soaked (20-mesh) sand bed with a 20° slope was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 5). Near the lower end of the stratum a small volume of larger (10-mesh) sand grains was filled with oil and covered with water-soaked shale. This was allowed to remain for one week and no movement of the oil had taken place. Then glass tubes were inserted into the sand at either end of the box. Water was pumped out of tube No. 1 at the higher end of the sand bed and at the same time water was allowed to run into tube No. 2 at the lower end. This was continued until the amount of water forced through the sand was several times its volume. No movement of the oil resulted. The accompanying photograph, Fig. 6, was taken after the experiment.

[1] These figures are rough approximations from data of Johnston and Adams (*ibid.*); also Harkins, Davies, and Clark, *Journal American Chemical Society*, XXXIX, No. 4 (April, 1917), 531.

This experiment is cited to show that oil does not migrate up the dip due to specific gravity differences, nor is it forced upward by circulating water.

On the outcrop the sands in the oil-bearing formations are not continuous but lenticular. By careful study of sands from well logs in different pools of the mid-continent field, the lenticular property of the sands becomes more evident. Water analyses

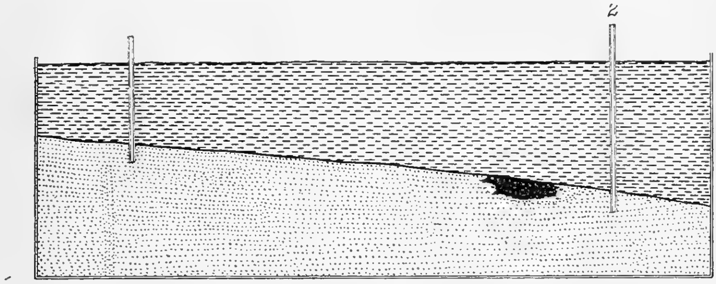


FIG. 5.—Diagram of apparatus for experiment showing no movement of oil in sand

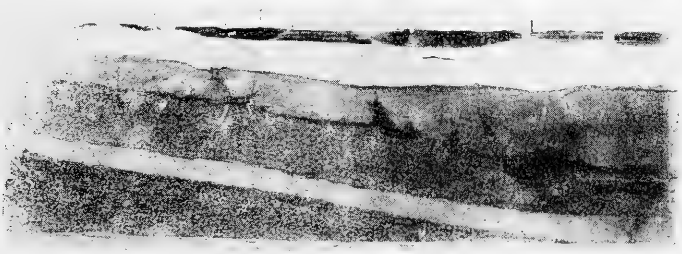


FIG. 6.—Photograph of apparatus used in Experiment 3, showing the oil remaining in the sand where it was originally placed.

also corroborate this fact. Results from four hundred water analyses to date point to the fact that each sand lens carries a definite water, uniform throughout and differing in some respect from the water of another lens. These waters are probably connate sea waters uncontaminated by surface water. In nearly pure silica sands the water differs little from sea water. In limy members or where other soluble minerals are noted the water is much higher in total solids than sea water. The present work seems to indicate that the change from normal sea water can be accounted for

by the minerals in, and surrounding, the water horizon. If the water shows no connection between different lenses in a sedimentary series, surely continuous sands or porous zones cannot be expected and consequently the analyses check the impossibility of migration from one lens to the other.

The pressure on the oil as it exists in the porous stratum is the same as that on the water which previously occupied the space. A volume of water replaces approximately an equal amount of oil, consequently the pressure in the reservoir remains the same. When the relation of oil to advancing water is such that the oil may be trapped and forced forward by capillary water, considerable pressure may accumulate on the oil due entirely to the capillary action of the water. Such conditions would be local if ever present and of little importance in commercial oil pools.

Pressures on fluid in an oil sand are often spoken of as "rock pressure" or "gas pressure." Neither term exactly defines the accumulated pressure on the fluid. The maximum static pressure available in any porous zone is a function of the size of the openings around that stratum. The determining factor is the capillary resistance of the water in the adjoining small openings. This factor depends upon the character of the sediment and the amount of compactness of the same. As the beds are more deeply buried, the shales become more compacted, and consequently the maximum available pressure in a given reservoir would be increased with depth. In this way there is a relation of maximum pressure to depth in the upper 10,000 feet of sediment. However, pressures do not necessarily increase with depth as would be indicated by the term "rock pressure." The amount of water originally in the reservoir and the tightness of the surrounding shales are other factors which may greatly change any relation of accumulated pressures to depths. A buried sand deposit may be completely filled with water and surrounded by a very fine shale, so that a small amount of settling[1] would increase

[1] In this paper it is assumed that settling of the strata has caused the fluid pressure in water sands of most of the mid-continent oil pools. With various degrees of saturation in sands of irregular sedimentation, the resulting fluid pressures after settling would be quite variable and irrespective of depth. Such is the case through-

the pressure on the water over that of a deeper sand, which might not have been so nearly saturated nor surrounded by so fine a shale.

The following estimate is made to show that the amount of oil in any producing field could have been derived entirely from shales immediately surrounding the oil sand. A series of shales aggregating 10 feet of bituminous sediment, yielding 25 gallons to the ton would furnish 17,000 barrels of oil per acre. Assuming a 25 per cent extraction, the acre yield would be over 4,000 barrels. The average acre yield in Oklahoma and Kansas ranges from 2,500 to 3,000 barrels. In case of 30,000-barrel-acre yield, which is a rare exception, the total amount of oil, considering a 25 per cent extraction, could be had from an acre bed of shale aggregating 50 feet of bituminous material yielding 40 gallons to the ton. Large acre yields are probably due to concentration in the sand along zones of exceptional openings, and the oil might have been drained from an area of several acres.

CONCLUSION

The foregoing evidence leads to the following conclusions:

1. Bituminous shales are in close relationship with the producing sand of an oil field.

2. This bituminous material is in solid form and is only changed to petroleum in local areas of differential movement.

3. After such a change is made, the accumulation of oil into commercial pools is accomplished by capillary water; and this interchange only takes place in local areas where the oil-soaked shale is in direct contact with the water of the reservoir rock. Such conditions are explainable either by joints or faults.

4. After the oil once reaches the sand, some adjustment takes place until the oil has found the larger openings and then it remains there indefinitely.

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out the Pennsylvanian rocks of Oklahoma, Kansas, and Texas. Moreover, in a number of cases the water may be reduced or exhausted by pumping the same as the oil, and the decline in production is according to the regular PV curve, showing that the pool is not connected with a source of supply, but has a definite volume in a definite space.

5. The amount of oil in any field could have been derived from normal bituminous shales in close proximity to the pay horizon.

6. These five statements also lead to another general conclusion, that areas of maximum differential movement are in accord with anticlinal structures. It has been noted from a study of the majority of pools in the mid-continent field that the maximum sub-surface faulting is found on the flanks and sides of the anticlines, and that the best production runs in trends parallel to the faulted zones. It has also been noted in a number of cases that production which is not related to marked anticlinal or dome structure bears the same close relation to sub-surface faults.[1]

The author is indebted to many co-workers in the sub-surface branch of the geology department of the Empire Gas and Fuel Company, who have diligently collected and compiled information. Especially is acknowledgment made to Mr. Gerald E. Moser for the diagrams in this paper; to Mr. E. A. Trager for aid in the experiments; to Dr. L. C. Snider for suggestions and criticisms in the work; and to Mr. Everett Carpenter, whose advice and counsel have made the investigation possible.

[1] Detailed data for the basis of these statements are necessarily considered confidential and cannot be published at this time. It is hoped that this material may sometime be available so that a paper discussing the details of various producing structures can be published.

SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE PRE-CAMBRIAN OF NORTHERN QUEBEC

H. C. COOKE

PART III

CORRELATION

In this region, where the sedimentary series do not form any large or continuous sheet, but are found merely as comparatively small remnants separated by wide areas of intrusive granite, it is obviously impossible to make an unquestionable correlation. If in some yet unexplored district there should be found large continuous sheets of sediments which might serve as definite horizon markers over a large area, as the Cobalt series does in the Cobalt-Sudbury-Lake Huron district, a good correlation may eventually be obtained. But under present conditions the criteria on which we must rely for correlation purposes are (1) petrographic similarities; (2) similar geological successions; (3) similar deformations; (4) similar relations to older and younger formations.

PONTIAC-MATTAGAMI-BROADBACK-BROCK SERIES

The patches of sediments known at present under the local names Pontiac, Mattagami, Broadback, and Brock series have strong petrographical similarities. In each the principal rock is a schist which is probably the metamorphosed equivalent of a more or less impure sandstone or sandy shale. It is now composed of quartz and ferromagnesian mineral, with a little feldspar; the ferromagnesian mineral is usually biotite, which locally is replaced by muscovite or hornblende. The muscovite schist probably represents an originally fairly pure sandstone, and the hornblende schist a ferromagnesian sand. The more acid types may have derived their material largely from granitic sources, the more basic types from the basic lavas. The mica schists

grade toward the base of the series into arkoses, greywackes, and conglomerates, which are of essentially the same composition as the schists above them, and differ only in their coarser grain.

This greywacke-like composition indicates that in each of the widely separated areas the sediments were derived by fairly rapid disintegration and erosion of older rocks, without extended decomposition of their constituents by atmospheric weathering. Had decomposition been complete and erosion slow, a better separation of the products of disintegration would have taken place, with resultant deposition of a normal sandstone-shale series. The band of quartzite found in the Kenoniska area is the only one observed in which fairly good segregation of the sedimentary material has taken place; yet its significance is not great, as the bed is thin and the quartzite very impure.

The petrographic similarities indicate that the sediments of the different areas were derived from similar sources, and that similar conditions of weathering and erosion were operative at the time each was laid down.

The succession of the different rock types also affords some evidence for correlation. At the base of each series is a conglomerate bed several hundred feet thick. The composition of this conglomerate is in every case similar—pebbles of granite and the underlying series of basic lavas, with their associated tuffs, cherts, and intrusives, imbedded in an impure sandy matrix. Above this, except in the Mattagami area, lies a coarse-grained arkose, greywacke, or grit, which passes upward into finer-grained material of much the same composition, now metamorphosed to mica schist. In the Mattagami area the conglomerate passes into the upper schist by a decrease in the size and number of the pebbles, without the intervening band of arkose; in the Kenoniska area a narrow band of impure quartzite lies between the arkose and the mica schist.

The succession is one which indicates an almost identical history of deposition in each of the areas under consideration. If the series is of marine origin, the history is one of deposition in a gradually deepening sea or of a subsidence of the land from which the sediments were derived. The absence of shale and

limestone members in every case is also significant of the prevalence of similar conditions of deposition over the whole region.

Structural similarities form perhaps the best evidence for the correlation of these patches of sediment. Each area is a remnant of a close fold, and the amount of deformation during folding was approximately the same in all. On the flanks of the folds the whole body of rock has been converted into schist, even the competent basal conglomerate. The pebbles of the conglomerate in each case have been flattened and sheared, the softer stretched to mere strings, while the hard granites have suffered very little. The axes of the folds show remarkable similarity in strike. The general strike of the Pontiac area is east-west; of the Mattagami area, N. 80° E.; the axis of the Kenoniska and Lucky Strike folds strike S. 75° E.; of the Brock fold, N. 85° E. These variations in strike are very small, considering how widely the districts are separated from one another, and the conclusion therefore seems justifiable that all of these sediments preceded, and were deformed by, one period of regional stress. As the region has been gently cross-folded, the variations in strike most probably are due to this, though perhaps also in part to disturbance by the later intrusion of the granite batholiths.

The different patches of sediments are similar in their relations to the older lava series. In almost every case it has been shown that the sediments rest unconformably on the lava series, since the basal conglomerate contains rounded pebbles of all the underlying rocks. As to the nature of the unconformity, a close parallelism of strike and dip obtains between the two series, indicating either that they were folded at one time or that a possible earlier gentle folding of the lavas was obscured by more intense shear after the sediments were laid down. In the case of the Kenoniska and Lucky Strike areas, the basal conglomerate was observed to rest on different types of rock from point to point, but whether this was due to differential erosion of the underlying rocks previous to the deposition of the conglomerate or to original irregularities of deposition in the underlying series was not determined with certainty. It is believed, however, to have been due to erosion, since in the case of the Lucky Strike area

the conglomerate at its most easterly observed contact rests upon garnetiferous mica schists, which are believed to be the metamorphosed equivalent of a once widely distributed sediment, the Nemenjish series, while farther to the west it rests directly upon basic lavas. In addition, the presence of the thick basal conglomerate indicates that the erosion of the underlying series was great before the deposition of the upper. In the undeformed conglomerate of the Kenoniska area, none of the basic pebbles possess schistosity; so that the lava series could not have undergone serious deformation before the conglomerate was laid down.

The similarity of the relations which prevail among the different patches of younger sediments toward the older series of lavas and sediments still further strengthens the probability that these patches originally formed part of a single widespread formation. The unconformity appears to be one of erosion mainly, with little or no structural discordance.

As regards the relations of the sediments to younger formations, the only younger rock in contact with all of them is the granite, which in each case intrudes them. As there is no sedimentary rock younger than the granite in the region, by which its age may be checked, the granite does not afford any adequate datum plane for correlation purposes.

Summary.—It has been shown that in the patches of sediments now known under the local names of Pontiac, Mattagami, Broadback, Lucky Strike, and Brock series, there are several striking similarities: (1) The character of the sediments shows that they were in each case derived by the disintegration and erosion of a land area, which went on with such rapidity that the component minerals of the eroded rocks were not highly decomposed; as a result, the sediments are not characterized by a normal sandstone-shale alternation, but are of a greywacke or arkose composition throughout. (2) The absence of the metamorphosed equivalents of limestone or shale, of which latter sediment there must have been some quantity, indicates fairly shoal water or subaërial conditions during the deposition of each series. (3) The succession in each case is similar; a conglomerate lies at the base, overlain by finer-grained material, arkose or greywacke, of essentially the

same composition, which in its turn is overlain by biotite or hornblende schists, representing similar material in a still finer state of subdivision. The succession indicates a similar history in each case. (4) The relations of each body of sediments to the underlying lava series appears to be one of erosional unconformity; if structural unconformity also exists, the discordance is slight. Thus the period elapsing between the outpouring of the lavas and the deposition of the sediments was characterized in each case by gentle epeirogenic movements only, not by intense orogenic movement. (5) The close parallelism of the axes of the major folds of the different areas indicates that all were deformed either by the same force or by successive forces directed along the same lines; while a study of the effects of shear on the different folds shows that each body of sediment was deformed to about the same extent. These two lines of evidence indicate that all the sediments were folded at the same time, and by stresses of much the same strength. (6) All the sediments have been intruded by granites, which, though not proven to be of the same age, have not as yet been shown to be of different ages.

While, as previously stated, an entirely reliable correlation in these pre-Cambrian rocks cannot be made in the absence of a continuous sedimentary datum plane, nevertheless the foregoing evidence indicates such a uniformity in the history of these scattered patches of sediments that it appears highly probable that they are remnants of a single, once widely distributed formation or series. So far as now known, this series may have been deposited under marine conditions and have formed a continuous sheet, or under continental conditions in separate settling basins. As the time has not yet arrived for the correlation of these sediments with other ancient sediments to the south and southwest, such as the Timiskaming, Sudbury, and Hastings series, the writer would apply a single local name to all those under discussion, simplifying the nomenclature by the elision of the various local names already applied. The name Pontiac series, applied by M. E. Wilson in 1909 to the sediments of the first discovered belt to the south, has precedence; but in view of the doubt as to the composition of Wilson's Pontiac series, as outlined on page 200,

the name "Mattagami series" will be used until the doubt is cleared up and the term "Pontiac" re-defined, if necessary. In the remainder of this paper the term "Mattagami series" will therefore be used to include the original Mattagami series, the Broadback, Lucky Strike, and Brock series, and the conglomerate-arkose portion of the Pontiac series to the south.

Age.—The Mattagami series has been shown to consist of scattered patches of sediments, all of which are older than a great orogenic movement and a period of granitic intrusion. In the southwest corner of the region under discussion, the Mattagami series is overlain by the flat-lying Cobalt series, which rests on a peneplain that bevels the Mattagami series, the intrusive batholiths of granite, and the older lavas indiscriminately. A very long period of erosion must have ensued therefore between the end of the deposition of the Mattagami series and the commencement of the deposition of the Cobalt series. The Cobalt series has recently been shown by W. H. Collins[1] to be of the same age as the upper part of the original Huronian series of the north shore of Lake Huron. It is separated there from the lower part of the Huronian, which Collins has termed the Bruce series, by an unconformity, represented by the erosion of some 1,600 feet of sediments and a gentle folding. The Bruce series has been shown by Collins[2] to be very similar in the character and succession of its members to the Lower Huronian of the Marquette region. The erosion plane dividing the Cobalt series and the older rocks in northern Quebec passes southward beneath the Cobalt series in the Cobalt district, and beneath the Bruce series in the Lake Huron district. It may safely be stated, therefore, that the Mattagami series is of pre-Bruce age, and therefore probably pre-Lower Huronian, and that it antedates the Bruce by an interval sufficient for orogenic forces to raise a mountain range of unknown height, and for the forces of erosion to reduce this range toward its southern side at least where the Bruce series was deposited, nearly to base-level.

[1] W. H. Collins, *Geol. Surv. Can., Museum Bulletin No. 8*, 1914.

[2] W. H. Collins, memoir in preparation.

NEMENJISH-GRENVILLE SERIES

A series of rocks which are the metamorphosed equivalents of clastic sediments has been termed the Nemenjish series in the foregoing pages. They attain their largest extension in the contiguous Windy Lake and Nemenjish areas. These rocks are believed to be the northern equivalent of the Grenville series.

The primary basis for this tentative determination is petrographic. It is recognized clearly that petrographic similarities as a rule form a most insecure foundation for correlation; but the petrographic peculiarities of these rocks are so marked and so different from those of any other rocks observed by the writer in the pre-Cambrian of Ontario or Quebec that they afford unusually good evidence for this purpose. The major portion of the rocks, above the basal beds, are highly garnetiferous. They consist of rather fine-grained, light grey mica gneisses or schists, and greenish-black hornblende gneisses, crowded with small, light pink garnets. The garnets in the mica gneiss are usually small, 1–2 mm. in diameter; those in the hornblende gneiss usually somewhat larger, 3–5 mm. in diameter. *Garnetiferous types probably average at least 50 per cent of the total bulk.* No such bulk of garnetiferous rocks is found in any other pre-Cambrian series. Garnetiferous types, usually garnetiferous hornblende schists, occur locally in the altered basic lavas, often termed "Keewatin," and also in the Mattagami series, but invariably in minor amount, less than 1 per cent. The writer therefore considers this criterion as a reliable one for correlation purposes, until it shall have been shown that another formation with similar bulk characteristic exists in the pre-Cambrian shield.

The Grenville series extends north of the Ottawa River at Ottawa for approximately 140 miles, almost to the junction of the east and west branches of the Gatineau River. It is bounded on the north by a great batholith of granite intrusive into it. A section made by the writer in 1916 down the Gatineau River from the National Transcontinental Railway to Ottawa showed that within the boundaries mentioned above the continuity of the series is unbroken, except by relatively small granitic

intrusions. Over a distance of about twenty miles south of its northern boundary the Grenville contains little crystalline limestone but is composed almost entirely of altered clastics, largely garnetiferous, of types identical or almost so with the Nemenjish series. Farther to the south, where crystalline limestone forms a large proportion of the Grenville, much of the remainder is composed of garnetiferous mica gneisses like those of the Nemenjish series.

A gap of about 140 miles exists between the Nemenjish series and the Grenville, occupied by a great batholith or batholithic complex of granite, which has an east-west extension from near the Bell River at least to Lake St. John, about 250 miles. The correlation of the two series across this belt of granite would appear at first sight a hopeless task; but it is rendered possible by the fact that the eastern end of the batholith is not deeply eroded, in fact is apparently barely unroofed. Across its whole width[1] thousands of inclusions of the Nemenjish or Grenville rocks are present, of all sizes and in all stages of digestion. These are so numerous that it is rare to find a single small outcrop of granite without undigested inclusions whose original nature is recognizable. In size the inclusions vary from small lumps a few inches or feet in diameter to large bodies several miles in length, which are probably true roof pendants. In freshness they vary from sharp-angled bodies with little or no trace of the solvent action of the granite to completely dissolved forms now represented by garnetiferous micaceous bands in the gneiss. A very characteristic trade-mark of the interaction of granite and sediment is the presence of garnet, which seems to have dissolved during the digestion of the sediment and subsequently to have recrystallized with little or no change. The formation of such digested products is so well shown in all its stages that even the end products of the reaction might safely be taken as evidence

[1] The sections studied by the writer, where such large numbers of garnetiferous inclusions were observed, were those of the St. Maurice River, from the Transcontinental Railway to Sandy Beach Lake, and thence northward across the Height of Land to Askitichi Lake; and from the Hudson Bay post at Kikendatch across to the headwaters of the Gatineau, and down the Gatineau. Farther to the west erosion appears to have removed greater thicknesses of granite; correspondingly the number of inclusions become smaller toward the west, and the proportion of those which have undergone complete or fairly complete digestion increases.

of the former presence of the sediments; but it is not necessary to rely on these as there is a sufficiency of the comparatively unaltered fragments for purposes of recognition. The highly garnetiferous character of the greater number of them renders their derivation from the Nemenjish or the Grenville series almost indubitable.

Summary.—The writer bases the correlation of the Nemenjish series with the Grenville series on the following facts: (1) The Nemenjish series possesses unusual petrographic characteristics, in that approximately 50 per cent of the rocks of the series are garnetiferous. (2) The granite batholith separating the Nemenjish and the Grenville series is loaded with recognizable inclusions of these peculiar garnetiferous schists. (3) The composition of the Grenville on the southern border of the granite batholith is identical with that of the Nemenjish series, i.e., garnetiferous mica and hornblende gneisses, with a little crystalline limestone. This passes to the south into Grenville of normal composition by increase in the amount of limestone, without much change in the character of the altered clastic members.

Relations to older formations.—The relation of the Nemenjish series to the lava series appears to be one of perfect structural conformity, although this determination is weakened by the fact that the contact was observed at one place only. As described, the sediments were found resting on the old surface of a basaltic lava flow, and with the same dip and strike as the lava. At the contact the sediments were thin beds similar to the tuffs elsewhere observed interbedded with the lavas; but these became mingled with beds of sediments similar to the overlying material a short distance above the base, and within a few hundred feet were entirely replaced by them. When these sediments were first seen, it was supposed that they probably belonged to the Mattagami series, and a very careful search was made along the contact with the lavas for evidences of unconformity, but none were found. There is not a trace here of the conglomerate which uniformly lies at the base of the Mattagami series, and appears to be at least 300 feet thick wherever it has been possible to measure it. There is no evidence of the presence here of any large

fault, which might have brought the two series into intimate contact. It would appear therefore as if there was no discordance, structural or erosional, between the sedimentary series and the underlying extrusive rocks.

The problem presents itself, however, of explaining why the Nemenjish sediments here rest upon basalts, which have been shown to form elsewhere the basal rocks of the lava series, rather than upon its higher members. On the creek flowing from Little Nemenjish Lake to Obatogamau Lake, five miles to the east, the sediments overlie andesites, although the contact is not exposed.

Two hypotheses present themselves. There may have been a period of erosion intervening between the extrusion of the lavas and the deposition of the sediments, so that where the sediments rest on the lower members the younger lavas may have been removed by erosion; or the younger lavas may never have been extruded in these localities. The first hypothesis appears inadmissible, on account of the perfect conformity and lack of any trace of basal conglomerate or coarse basal sediments. If the second hypothesis be true, then some of the lower beds of the Nemenjish series must be equivalent in age to the upper lava flows, unless conditions were such that no sediment was deposited during the period intervening between the extrusion of the earliest and latest lavas. We might therefore expect to find at some point an interbedding of the sediments with the higher lava flows. This is actually the case on Kaopatina Lake, where a thin flow of rhyolite porphyry in interbanded with the sediments. In this case, the beds with which the flows are interbanded are not of true clastic material, but appear to be made up in part of cherty material, perhaps a chemical sediment, and in part of fine-grained, rather basic material, perhaps volcanic dust or the first products of erosion of the lava fields. In the critical section of the Opawika River above Kaopatina Lake, beds of similar composition were observed to lie at the base of the Nemenjish series, and to grade up into it by a gradual increase in the proportion of normal clastic material.

It seems probable therefore that the whole region was not covered by uniform sheets of lava of the same composition, but

that as might be expected, the extrusions were more or less localized, so that the Nemenjish series may lie from place to place on different types, but still maintain conformable relations. Further, it appears that the sedimentation was slight during the whole extrusive period, and largely confined to deposits directly or indirectly from volcanic sources. Lava flows may be interbanded with these sediments, but the extrusion of these was complete before the true clastics became large in amount, as the two have never been found interbanded.

Relations to younger formations.—Since the Nemenjish series rests conformably on the lavas in the Windy Lake area, and the Mattagami series rests unconformably on the lavas in the Brock and other areas, it might be supposed that the Mattagami series is younger than and unconformable on the Nemenjish series. This conclusion assumes that the lavas in the different areas are of the same age. Direct field evidence bearing upon the relation of the two sedimentary series is very scanty. The only areas furnishing such evidence are the Kenoniska and Lucky Strike areas, where garnetiferous mica schists are found lying between the Mattagami basal conglomerate and the underlying lavas. The petrography of these rocks makes their correlation with the Nemenjish seem probable, and they lie unconformably beneath the Mattagami series.

The Nemenjish-Grenville series is intruded by all the plutonic rocks of the region, and is therefore older than all. An older granite intrudes it in the vicinity of Lake St. John. Later, it was cut by great masses of anorthosite. Finally, it was cut and, in this region, almost entirely stopped away and digested by the great batholithic intrusions of granite which followed the deposition of the Mattagami series.

LAVAS

The lavas of the region under discussion appear to be of a single age, so far as the evidence at hand indicates. They are very similar in their petrographic character and in the extent of their metamorphism. Wherever their succession has been worked out, it is the same; basaltic lavas form the lowest exposed beds, overlain successively by andesitic lavas, andesitic tuffs, and

rhyolitic lava or tuff.[1] Wherever sediments of Nemenjish age have been found the lavas underlie them conformably. Whereever patches of the Mattagami series occur, they overlie the lavas with unconformity. Wherever anorthosite masses outcrop, they intrude the lavas.

As these lavas, like the Mattagami series, underlie the great erosional peneplain that underlies the Cobalt series, it is possible that they are to be correlated with the lavas in the Cobalt district, which are there known as "Keewatin" and which occupy a similar stratigraphic position. There is as yet, however, little or no evidence for correlating these lavas with the Keewatin of the north and south shores of Lake Superior. The local name of Abitibi volcanics will therefore be extended to apply to the lavas in this whole region. This name was first applied by M. E. Wilson in 1909 to the lavas in the Kewagama map-area, in the southwestern part of this region.

ANORTHOSITES

Anorthosite and anorthositic gabbro do not appear to any large extent within the region under discussion. A mass of considerable size is found on the Bell River, near Mattagami Lake, another on Chibougamau Lake. Smaller masses are found on the Opawika and Chibougamau rivers; there is an immense mass in the vicinity of Lake St. John. To the east and south of Lake St. John, the amount of anorthosite is much larger; it is also present in large amount in the Adirondacks.

Since anorthosite may be formed as a differentiate of any gabbroid magma under suitable conditions, and since it so happens that the anorthosite masses are not as a rule in contact with a sufficient number of sedimentary formations for their age to be closely determined there is little or no evidence that they may not be of more than one age. However, the occurrence of such great masses of anorthosite has been rare throughout geologic history. Hence it is considered highly probable that all of the anorthosite belongs to a single period of igneous activity and owes its origin to some common cause.

[1] It may be here mentioned that the writer's work of 1917–18 has shown that the simple succession described for the lavas of northern Quebec does not prevail in the Montreal River district of northern Ontario.

The age of the anorthosite, while not definitely fixed, may tentatively be placed as post-Grenville and pre-Mattagami. In the Lake St. John district it has been found to intrude the Grenville, and also to intrude an earlier granite which also intrudes the Grenville. It is itself intruded by the later granite that cuts the Mattagami series. It has never been found in direct contact with the Mattagami series. A mass of anorthositic gabbro on the Bell River intrudes the Abitibi volcanics but does not rise as high as their contact with the Mattagami series. In the Lucky Strike area a single pebble of what was supposed to be anorthosite was observed in the basal conglomerate of the Mattagami series. This pebble could not be got out of the matrix for microscopic study, however, so that its exact determination is uncertain. The age of the anorthosite can, therefore, only be placed tentatively as pre-Mattagami.

GRANITES

In the vicinity of Lake St. John, J. A. Dresser[1] has reported the presence of granites both earlier and later than the anorthosite there. To the northwest of the lake all the granite observed is later than the anorthosite. To the south and east of the lake, Adams[2] has reported that the granite is earlier than the anorthosite. In New York state, Cushing, Kemp, and Smyth state that the anorthosite is later than the gneisses which intrude the Grenville series. The existence of granites of two ages therefore seems to be fairly definitely established. The earlier of these seems to have been confined in its distribution to the south and east of Lake St. John; in age it postdates the deposition of the Grenville series and antedates the intrusion of the anorthosite masses. The later granite was intruded mainly throughout the region to the north and west of Lake St. John, though it is also found in small amount to the south and east. In age it is pre-Cobalt, but is later than the anorthosite intrusions and the deposition of the Mattagami series.

[1] *Geol. Surv. Can., Mem. No. 92,* 1916.

[2] *Geol. Surv. Can., Ann. Rept., New Ser.,* VIII (1897), Part J.

[*To be continued*]

A PLANIMETER METHOD FOR THE DETERMINATION OF THE PERCENTAGE COMPOSITIONS OF ROCKS

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The great objection to the Rosiwal method for determining the composition of rocks lies in the nerve-racking necessity of continually reading the stage-micrometer, and the length of time required for the process. In a recent paper in the *Journal of Geology,* Shand[1] described a mechanical stage by the use of which very few readings are necessary. An instrument of this kind undoubtedly would greatly reduce the labor of computing the composition of a rock and tend to make the method more popular. Unfortunately few laboratories are likely to have such a stage; but with the equipment on hand in most institutions, measurements more rapid and possibly more accurate may be made.

Many years ago Delesse[2] determined the compositions of rocks by tracing, on oiled paper, the outline of each component as shown in polished slabs. After coloring his drawing he pasted it on tin foil, cut apart and sorted the different components, soaked off the paper, and weighed the tin foil. Later, Sollas[3] applied the method to thin sections by using a camera lucida, and Joly[4] used photomicrographs. Since Rosiwal[5] introduced his method of linear measurements in 1898, it has been the system commonly used.

[1] S. J. Shand, "A Recording Micrometer for Geometrical Rock Analysis," *Jour. Geol.,* XXIV (1916), 394–401.

[2] A. Delesse, "Procédé méchanique pour déterminer la composition des roches," *Comptes Rendus,* XXV (1847), 544–45; see also article, "Procédé méchanique pour déterminer la composition des roches," *Ann. d. Mines,* XIII (1848), 379–88.

[3] W. J. Sollas, "Contributions to a Knowledge of the Granites of Leinster," *Trans. Roy. Irish Acad., Dublin,* XXIX (1887–92), 471–73.

[4] J. Joly, "The Petrological Examination of Paving-Sets," *Proc. Roy. Dublin Soc.,* X (1903–5), 62–92.

[5] August Rosiwal, "Über geometrische Gesteinsanalysen," *Verh. d. k. k. geol. Reichsanst.,* Wein, 1898, p. 143.

The method described below is based on surface measurements. As will be shown, these are proportional to volumes in any uniform, non-banded rock, irrespective of the shape of the individual components.

Place a camera lucida over the eyepiece of the microscope and block up a drawing-board at the side so that the field of view is not too large, say four or five inches in diameter. Tilt the microscope or incline the plane of the paper until the drawing is not distorted. This may be determined by tracing the projection of a circle or square upon the paper and measuring it in several directions. If no object-glass with circle or square is at hand, place an ordinary object-scale successively vertically at the right and left of the field of view, and horizontally at the top and bottom, and lay off equal distances in the projection. If equal divisions on the scale are equal everywhere in the drawing, the plane of projection is at the proper angle or the microscope is properly tilted.

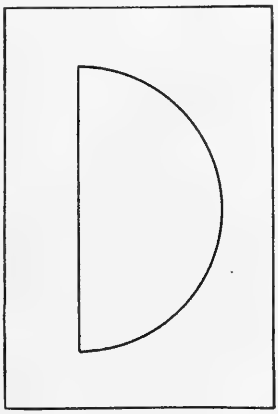

Fig. 1

Place one edge of a thin straight-edge of wood, celluloid, or cardboard on the drawing-board along the projection of the vertical cross-hair as seen through the camera lucida, and fasten it with thumb tacks. This is to serve as a guide for the stylus of a planimeter, as described below. Instead of a straight-edge, the writer uses a piece of celluloid about 1 mm. thick, in which is cut a semicircle (Fig. 1) exactly the size of the field of view ($4\frac{1}{2}$ inches in his microscope with a 31-mm. objective).

Select the objective most suitable for the particular rock section in hand; the lower the power, the better. Place a typical area in the field of view, and make on the cover-glass, on the line of the vertical cross-hair, a mark in red ink to indicate the starting-point. Place a planimeter on the drawing-board in such a position that the base will not interfere with the projection of the section as seen through the camera lucida.

Place the stylus of the planimeter at the top of the field of view and on the vertical cross-hair (Fig. 3, *A*). The writer replaces the ordinary stylus by a heavy wire bent as shown in Fig. 2, so that the end of the planimeter bar will not interfere with a view of the end of the needle point. Adjust the length of the planimeter bar so that when the stylus is moved around the semicircle (Fig. 1), that is, half the field of view, it will register exactly unity (10 or 100). This adjustment, of course, is not necessary, but by making it all readings are in percentage values without conversion; otherwise it is necessary to reduce the sum of the readings to 100.

Fig. 2

Record the reading of the planimeter or set it to zero by rotating the wheel. If the bar has not been set to read 100 for the field of view, move the stylus around the periphery of the field in the proper direction, right or left, to record additions, and read again. The difference will give the area of a single field. Again set the planimeter at zero, and, beginning at *A*, move the stylus along the straight-edge to the periphery (Fig. 3, *B*) of the first grain of the particular mineral chosen for the first determination, say biotite in granite. Trace the outline of this grain and *remember always to move the stylus in the same direction of rotation.* It will be necessary in the first readings to lift the stylus point on top of the straight-edge to record the left-hand portion of the mineral. Having returned to the point *B*, without reading the planimeter move along the straight-edge to *C* on the periphery of the next grain of biotite *lying on the line of the vertical cross-hair,* and move around it in the same way and in the same direction back to the point *C*. If the mineral of the kind being measured lies in the center of the circle (Fig. 3, *D*), it is always to be measured in

Fig. 3

the first series of readings for that kind of mineral so that it may not be forgotten.

Rotate the stage of the microscope to the left until the left margin of another grain of biotite is *just tangent* to the cross-hair. Though the point D at which the stylus rested on the outline of the last mineral measured is moved to D' (Fig. 4) the stylus in the projection, of course, still rests at D. From this position move upward or downward to the periphery E of the new biotite grain tangent to the cross-hair and trace its outline in the same direction as before. Rotate the stage until another grain is tangent to the cross-hair, trace its outline, and so continue until all of the grains of biotite in the section have been measured, and the red spot again lies on the vertical cross-hair. The object of rotating the stage of the microscope only so far as the point of tangency of each new grain is to avoid confusion and the repetition or omission of some fragment. Movements up and down along the straight-edge, being plus and minus, are not recorded when the stylus again rests at A. When all the grains of this species of mineral have been measured and the *stylus has been returned to the point "A,"* record the planimeter reading and subtract the preceding reading from it. This gives the total area of the first mineral measured. If there are any inclusions in a mineral they may be deducted by moving them to the point of tangency and rotating the stylus around them in reverse direction.

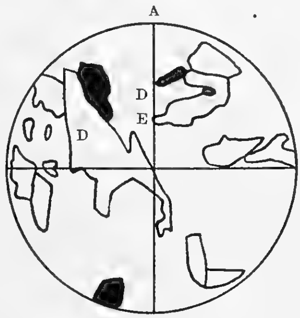

FIG. 4

Begin with the red mark on the slide again at the top of the vertical cross-hair and measure a second variety of mineral in the same manner as before, and so on until all the minerals are determined. It is usually well to measure the more pronounced or least abundant minerals first, leaving for the last the most abundant, least pronounced, or groundmass mineral. A slight error in the other readings will change the true percentage less

by leaving the most abundant mineral to the last and recording it as the difference. As a check, the last mineral should be measured and the sum of all the readings should be the same as that of the field of view.

In tracing the peripheries of the mineral grains, when they are very irregular, it is not necessary to follow their outlines absolutely; the little variations from one side to the other compensate. Furthermore, hackly ends may be averaged, long needles traced to half their length but twice their width, and so on, the results being usually more accurate than if the actual outlines are followed. Where there are a number of very small grains, as of magnetite, they may be estimated and a circle described by the stylus approximately equal to their sum. A little experience will show what may be done in the way of short cuts.

The number of fields of view to be measured in a rock slide depends upon its uniformity of texture, the mineral distribution, and the size of grain. With small grains and uniform distribution of minerals, a single field may suffice. With coarser grain or unequal distribution, it may be necessary to take as many fields as will cover the entire thin section, or it may be advisable to use several sections. If the mineral grains do not fill the field of view, or if there are pore spaces, it is only necessary to deduct the readings of these from the reading of the circle of the entire field of view and reduce the sum to 100.

The measurement of the dark minerals is easy, but the separation of the colorless minerals may give trouble. Before running the outline of one of these, it is usually well to swing off the camera lucida, insert the analyzer, and rotate the stage to various positions until the boundaries are clearly in mind; then, after replacing the camera lucida, place the edge of the mineral tangent to the vertical cross-hair as before and, with the nicols still crossed, trace the outline. The writer uses a Leitz microscope with simultaneously rotating nicols which makes it unnecessary to disturb the position of the stage; the nicols only are rotated until the mineral appears in its most pronounced color.

With crossed nicols, or when separating minerals of different refractive indices by partially closing the lower diaphragm, it

may become necessary to cut off some of the illumination from the paper. This, of course, is done by inserting the blue glass screens provided with the camera lucida. In other cases, when the light from the stage is too bright, the blue glass may be swung to that side, or, more simply, a blue glass may be placed over and parallel to the thin section and below the objective, or some of the light may be cut off by holding a finger before the mirror, by tilting it, or by partially closing the lower diaphragm. In some cases one method is best; in others, another. Sometimes the drawing or the mineral is made more distinct by simply holding the eye at a greater distance from the camera lucida.

THE BUTTE QUARTZ MONZONITE MEASURED BY PLANIMETER

The writer uses volume percentages for his determinations instead of weight percentages. For example, a rock is half-light and half-dark to the eye when the volumes are 50–50 and not when their weight percentages are 50–50. Thus a rock half plagioclase and half magnetite by volume would have the proportions 34.4 to 65.6 by weight. In the following table, therefore,

	Rosiwal Determinations by Four Different Students on the Same Slide Volume Percentages				Average of Preceding	Average of Following	Planimeter Determinations on Four Different Areas of Same Slide as First*							
							First Area		Second Area		Third Area		Fourth Area	
Quartz	14.80	17.24	18.07	17.24	16.84	18.4	22.9	22.0	17.5	18.0	18.1	17.9	15.1	14.8
Orthoclase	34.52	26.01	27.80	22.54	27.72	28.5	20.3	19.8	30.2	31.0	31.5	31.8	31.6	32.1
Plagioclase	34.52	45.50	38.67	42.46	40.29	39.9	46.8	47.2	36.6	36.0	34.1	33.9	42.7	41.8
Biotite	7.97	5.30	9.67	9.84	8.19	7.4	4.5	5.4	8.3	7.8	9.2	8.9	7.7	7.9
Pyribole	7.67	4.48	4.61	7.76	6.13	5.2	5.0	5.2	5.9	6.0	6.9	7.0	2.6	3.0
Magnetite	.44	.48	.55	.16	.41	.4	.1	.1	1.2	1.0	....	....	.3	.4
Pyrite, etc.	.07	.95	.58	.....	.40	.2	.4	.3	.3	.2	.2	.5	....	.....
	99.99	99.96	99.95	100.00	99.98	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*The volume percentages by the planimeter method here given are not to be compared with the weight percentages in the paper by Johannsen and Stephenson in the preceding number of this *Journal*, since they represent a single and not typical slide; namely, the one shown in the first column of Table III in that article.

volume percentages are used. The first four columns give the Rosiwal readings made by four different students on the same slide of Butte quartz monzonite; the fifth column is their average. The sixth column is the average of eight planimeter readings on four fields of the same slide. The similarity of each pair of readings is to be noted. The differences shown by the four fields are

not due to errors of reading but to actual differences in different portions of the slide, the rock being coarse enough to show such variations. It is true that the planimeter readings were all made by one person and not by different individuals, which may account somewhat for their similarity, though clearly showing that the error cannot be great. The averages obtained by the two methods are very similar in spite of the fact that some of the students' readings are clearly in error.[1]

The length of time required for a planimeter reading of a single field of a rock of the character of the one here used is about ten minutes or less. Using four fields, a complete determination can be made with ease in three-quarters of an hour, and without any great mental strain during the process.

RELATIONSHIP BETWEEN AREAS AND VOLUMES

In the discussion of the relationship between surface and volume measurements, the mistake has commonly been made of considering this as a comparison between d^2 and d^3 to D^2 and D^3, where d is the length of a side of a square representing the sum of all grains of the same mineral appearing in a section, and D the side of a square representing the entire surface. As a matter of fact, in a rock with uniformly distributed particles, this is not the relationship at all, for if the mineral grains under consideration were floated to one side of the cube they would make a thin tablet, one dimension (d_1) depending upon the abundance of the mineral, each of the other two equal to the side of the large cube (Fig. 5, D). In the Rosiwal method this is the way in which the minerals are to be considered as placed, and each Rosiwal reading from west to east includes the proper proportion of the mineral. The surface value is d_1D, not d_1^2, and the volume d_1D^2, not d_1^3. If one measures areas, the mineral may be considered floated to

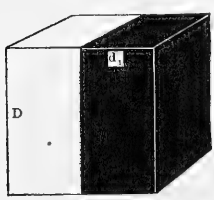

Fig. 5

[1] In explanation it must be said that the determinations here given were the students' first efforts with the Rosiwal method. The planimeter determinations are by the writer.

a vertical edge (Fig. 6) forming a vertical prism whose dimensions are d, d, and D; the value of d, of course, differing from the d_1 value but such that $Dd_1 = d^2$. The surface and volume values in each case, naturally, are the same. This may easily be seen by considering a solid built up of black and white cubes.

I. CASE OF CUBICAL GRAINS, UNIFORMLY DISTRIBUTED

a) Assume a cube, 10 inches to a side, built up of small black and white inch cubes, uniformly distributed. If the black–white ratio is 50–50, every other block must be black. Moved to one side so that all the black cubes are together (Fig. 5), the number at the surface will be 50, distributed in a rectangle whose sides are d_1 and D (5×10). Moved to one edge the 50 square inches of surface would appear as a square, seven cubes on a side and one left over; in other words, $d = 7.07+$. The total number of black

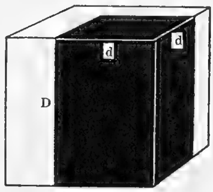

FIG. 6

cubes is 500; therefore the volume is not represented by d^3 ($=353.5+$) but by $d^2D = 50 \times 10 = 500$. The relationship, therefore, between the black minerals appearing at the surface to the entire surface is as $\frac{d^2}{D^2}$, while the volume relation of black to white is $\frac{Dd^2}{D^3}$ and not $\frac{d^3}{D^3}$. But $\frac{d^2}{D^2}$ and $\frac{Dd^2}{D^3}$ are equal; therefore the ratios of surface and volume measurements are equal.

b) If the ratio of black to white is very small, such as 1 to 10,000, it will not do to assume that the black mineral occurs as a single cube, whose volume is $\frac{1}{10}$-cubic inch, in a 10-inch cube of white, for that would vitiate the original assumption of uniform distribution of constituents. If we say that the ratio of surface to solid is as d^2 to d^3 it means that our mineral all lies in the top layer and is not uniformly distributed. It is comparable to saying that a topaz granite in which an accidental crystal of topaz occupies half the slide is half-topaz, while as a matter of fact there might be but a single crystal to a cubic foot. Consider, therefore, that the small amount of black mineral is uniformly distributed in

cubes measuring $\frac{1}{10}$ inch on a side ($d=\frac{1}{10}$ inch). If now all these small cubes be gathered along one of the vertical edges of the large cube, the portion of the black mineral of the entire block which will appear at the surface (Fig. 6) will be $d^2=(\frac{1}{10})^2$, and the black–white surface ratio will be $\frac{d^2}{D^2}=\frac{(\frac{1}{10})^2}{10^2}=\frac{1}{10000}$. That is, the black mineral forms .01 per cent of the surface. The volume ratio of black to white is $\frac{Dd^2}{D^3}=10\frac{(\frac{1}{10})^2}{10^2}=\frac{1}{10000}$. The volume ratio, therefore, is the same as the surface ratio.

II. CASE OF TABULAR PLATES, UNIFORMLY DISTRIBUTED

Let a, b, and c represent the ratios of length, breadth, and thickness of tabular dark constituents. If they are uniformly distributed the same number of flakes will be contained in each layer below the upper surface; consequently no matter what the thickness, Dab represents the volume of the black blocks, while D^3 represents the large block. The ratio of surface measurements to the whole is $\frac{ab}{D^2}$, and of volumes $\frac{Dab}{D^3}=\frac{ab}{D^2}$; consequently the two are equal.

With thinner flakes there would be more layers in the large cube, and with thicker, less. But no matter what the ratio of a to b to c, the surface percentage is the same as the volume percentage, *provided the grains are equally distributed.* Of course a laminated rock, with layer of different minerals, might be so cut that one slide would contain no dark minerals and one no light. A cross-section of such a slide, however, would give correct results, for the distribution at right angles to the slide is uniform.

III. CASE OF CLOSELY PACKED CYLINDRICAL RODS

This case is approximately the same as the preceding, for in one direction in the slide the mineral is continuous while in the other there is interstitial material. Sections should, therefore, be taken at right angles to the elongation. The surface ratio is $\frac{\pi r^2}{D^2}$, and the volume $\frac{D\pi r^2}{D^3}$. As before, the two are the same.

IV. CASE OF SPHERES CLOSELY PACKED AND SQUEEZED TOGETHER

When spheres are closely packed and are then squeezed together they tend to assume the form of dodecahedrons. A cross-section through such a mass will give a series of triangles. If b is the base of such a triangle and h its height, its area is $\frac{bh}{2}$. Nbh will be the area of the sum of such triangles and the ratio to the whole, $\frac{Nbh}{D^2}$. Since every parallel section will give an equal distribution of light and dark, the volume of dark mineral will be $DNbh$ and its ratio to the whole $\frac{DNbh}{D^3}$, which is the same percentage ratio as in the case of the surface measurement.

Thus, no matter what the shape of the individual mineral grains, if they are uniformly distributed the surface ratios are exactly the same as are the volume ratios; consequently surface measurements may be used to represent volume measurements in the determination of the composition of a rock.

GEOLOGY OF FLORIDA

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To those who have seen Florida but casually it may seem that the geology of the state is entirely obscured beneath the sand, soil, and vegetation of the prevailingly level surface. But to those who have looked more closely it is apparent that such is not the case. It is true that the problems of geology are made more difficult by the lack of frequent and continuous exposures, but they are not necessarily made impossible of solution. The numerous stream channels, railway and public-road cuts, drainage canals, and drilled wells afford records from which the stratigraphic succession and structure of formations may, with patience and persistence, be worked out. Fortunately many of the formations of the state are richly fossiliferous. Nowhere in the United States do the Tertiary and Quarternary formations contain a more abundant, more varied, or better preserved marine invertebrate fauna than in Florida. In this respect there is an embarrassment of riches. Dr. Dall in his study of the fossils of the Caloosahatchee marl, recognized in that formation alone the presence of more than 600 species of mollusks. Vertebrates, although as a rule not so well preserved as the invertebrates, are relatively numerous. No state east of the Mississippi, perhaps, contains so many Tertiary and Quarternary vertebrates as does Florida. Fossil plants, although less abundant than either invertebrates or vertebrates, are not wanting. It is seldom the case that a single formation holds both land and marine fossils, yet something of an insight into the interrelation of the marine invertebrates, land animals, and land plants is secured in the Florida Miocene and again in the Florida Pleistocene. In the study of the fossils, Florida is in many respects a state of exceptional opportunities.

TOPOGRAPHY AND ELEVATION

In topographic detail and surface configuration Florida is by no means lacking in variety. In this respect the state presents much greater diversity than would have been anticipated in view of the fact that the maximum elevation within the state scarcely exceeds 300 feet above sea-level. In the upland section of the state the intimate relation between topography and geology becomes apparent. The limestones under the influence of a heavy rainfall and an excess of humic acids in the ground water have dissolved rapidly, and when lying near the surface have produced a characteristic topography. The lowlands bordering the coast, on the other hand, have been but little affected by erosion, and in these areas the surface is perhaps but slightly modified from its original condition. Of the land area of the state, approximately one-half lies below the 50-foot contour line. This belt of land below the 50-foot contour includes all of the peninsula south of the northern end of Lake Okeechobee, and in addition a strip of varying width bordering the Atlantic and Gulf coasts. Aside from beach deposits and sand dunes, this belt of country is prevailingly level. The surface deposits are usually sandy, although, as will be subsequently indicated, limestones underlie considerable areas.

The higher lands of the interior of the state present for the most part topographic features that are difficult of description, owing to the apparent irregularity and lack of system of the hills and valleys. Over much of this area the topographic features are the result of the solution of the underlying calcareous deposits, and the prevailing surface configuration includes depressions or solution basins of varying size and depth, and hills of varying size and height. Within the area, the topography of which is controlled by underlying calcareous deposits, are two subdivisions which are worthy of special mention. These are the "sink-hole region," which lies chiefly along the west slope of the peninsula, and the "lake region," which lies for the most part near to or somewhat east of the center of the peninsula. In the sink-hole region the limestones lie at no great depth. The sinks which form as a result of the solution of the limestones, thus allowing the covering to fall in, usually reach

through to permanent water level, thus forming small circular lakes. In the lake region the calcareous rocks are covered to a greater depth. The lakes are usually circular in outline and are deep, with high banks. In extreme western Florida, including Escambia and Santa Rosa counties, the calcareous deposits are buried beneath the surface to such a depth as not to affect the topography. A similar region is found on the east bank of the Apalachicola River, including Gadsden and the northern part of Liberty counties. Under these conditions the topography is determined by the normal drainage courses.

CLIMATE, TEMPERATURE, AND RAINFALL

The climatic conditions of the state are appreciably influenced by the proximity to oceanic waters. This is especially noticeable with regard to temperature, rainfall, and humidity. The temperature is moderate, the rainfall moderately heavy, and the humidity high. The mean annual temperature near the northern line of Florida is about 67° F., while at Key West in extreme southern Florida the mean annual temperature is close to 77° F. By far the greater part of the state lies within an area which receives between 48 and 57 inches annual rainfall. In extreme southern Florida on the Keys is a small area in which the rainfall is much less, the average for the station at Key West being about 38 inches. On the other hand a small area in extreme western Florida and another along the South Atlantic Coast receives an annual rainfall approximating 60 inches. The average annual rainfall for the state as a whole is close to 54 inches. The rainfall is distributed irregularly throughout the year. The driest months are April and November, while the heaviest rainfall comes as a rule from June to September. Variation in rainfall is pronounced in Florida. This variation is due in part to normal seasonal variations, and in part to the influence of heavy tropical storms, especially those of the late summer and fall. These storms, or hurricanes, which fortunately are not of frequent occurrence, usually result in a heavy precipitation in the belt of country through which they pass.

The maximum recorded precipitation for one year in Florida is probably that of 1912, at which time the rainfall for the state was

64.88 inches (*Climatological Report*, 1912). The maximum for any one station during this exceptional year was 91.61 inches, at Molino in Escambia County. The maximum recorded rainfall for any one month at a single station is 31.26 inches, which is credited to August, although in July, 1916, the rainfall at Bonifay, in Holmes County, was 30.6 inches. The rainfall of a single storm lasting somewhat more than one day has been known to exceed 10 inches. The rainfall for a period of twenty-four hours is known to have been as much at a single station as 13.18 inches. As much as 3.90 inches is recorded as having fallen in one hour at Tampa in August (*Climatological Data*, sec. 84).

DRAINAGE

The drainage conditions in Florida are in some respects exceptional. In that part of the state in which limestones are near the surface, especially on the upland limestone section of the interior, the drainage is largely subterranean, although much of the water that thus enters the earth reappears through large springs which supply streams. In the limestone belt the rainfall enters the earth either directly through the surface materials or through disappearing streams which discharge their flow into porous rocks. The subterranean drainage is best developed in that part of the state known as the "lime sink" region, where aside from the main rivers there are few or no surface streams. Partial subterranean drainage, however, is characteristic of a very much larger area, and for the state as a whole the average for surface run-off is low.

The prevailingly level country over much of the state, together with porous soils, results in but limited surface wash. However, in the more hilly parts of the state the wash of road beds and soils under the influence of heavy rains is sometimes serious.

The streams of Florida for the most part have a slight gradient and are slow-moving. The drainage of the westward extension of the state is through numerous streams, of which the Apalachicola is the largest, having a general north–south direction. The drainage basins of the peninsula are for the most part ill-defined. The St. Johns River, which flows north, and the Kissimmee River, which flows south, receive much of the drainage of the Atlantic slope.

Entering the Gulf of Mexico from the western slope of the peninsula are a number of streams; among which are the Suwannee, Withlacoochee, Hillsboro, and Caloosahatchee rivers.

GEOLOGY

Florida lies entirely within the Coastal Plains province and the formations exposed at the surface are all of the Cenozoic era. The amount of limestone in Florida is relatively large; nevertheless, a very considerable quantity of sedimentary material, including sand, clay, and flint pebbles, was carried to the south and included in some of the Florida formations. The progress made in recent years in the study of the geology of Florida has made necessary a number of

TABLE OF GEOLOGIC FORMATIONS IN FLORIDA

		Feet
Pleistocene	Palm Beach limestone. Marine.	5–50
	Miami Oölitic limestone. Marine.	10–50
	Key Largo limestone. Marine.	75–100
	Key West limestone. Marine.	50–70
	Lostmans River limestone. Marine.	30–40
	Fort Thompson beds. Marine and fresh water.	0–20
	Unconformity in places (at least).	
Pliocene	Bone Valley formation. Estuarine.	20–100
	Alachua formation. Residual.	20–100
	Caloosahatchee formation. Marine.	10–25
	Nashua formation. Marine.	10–30
Miocene	Choctawhatchee formation. Marine.	30–50
	Jacksonville formation. Marine.	Thickness undetermined
	Alum Bluff formation. Marine; shallow water.	50–400
	Unconformity where Miocene overlaps Eocene.	
Oligocene	Tampa formation. Marine.	0–130
	Chattahoochee formation. Marine.	100–200
	Vicksburg formation. Marine.	20–60
	Unconformity in places (at least).	
Eocene	Ocala formation. Marine.	0–50
	Claiborne formation. Marine.	Thickness not known
	Unconformity.	
Cretaceous	Unknown.	
Comanchean	Known only from well cuttings.	

changes in the classification of the formations of the state. Of the formation names formerly in use, one or two have been discarded, and on the other hand several new names have been added. The classification which at present best represents our knowledge of the geology of the state is expressed in the table (p. 290). A recently discovered fact in regard to the geology of Florida is the presence of Comanchean formations forming the substructure of the peninsula and extending at least as far west as Tallahassee.[1] Scarcely less remarkable is the complete absence, so far as any records yet obtained indicate, of the Cretaceous formations (Upper Cretaceous). If any of these formations were present they were removed by erosion previous to the deposition of the late Eocene formations. Their absence in any case can be accounted for only by a long period, previous to the late Eocene, during which the Florida land mass stood above water-level. The earth structure by which this peninsular land mass was produced thus dates back at least into the Mesozoic period.

STRATIGRAPHIC SUCCESSION

COMANCHEAN FORMATIONS

The oldest formations that have been recognized in Florida are those encountered in well drilling and known at present only from well cuttings. The fossils found in these cuttings indicate the presence of Comanchean formations under all of the peninsula and a part at least of west Florida. The discussion of these formations together with the data from which they have been determined has been given by Dr. J. A. Cushman in the *Twelfth Annual Report of the Florida Geological Survey*. The thickness of the Comanchean underlying Florida has not been determined. The formations are chiefly limestone. The Cretaceous (Upper Cretaceous) is wanting in all deep wells of which record has been obtained.

EOCENE

The Eocene deposits are represented in Florida by the Claiborne and Ocala formations. The *Claiborne formation* comes into Florida for only a short distance on the Choctawhatchee River near the

[1] Joseph A. Cushman, "The Age of the Underlying Rocks of Florida as Shown by the Foraminifera of Well Borings," *Florida State Geol. Surv., 12th Ann. Rept.*, 1919.

Georgia-Florida border. Where exposed on the Choctawhatchee River this formation consists of a glauconitic calcareous sand rock, exposures of which are seen at intervals on the river banks for about one and two-thirds miles downstream from the Georgia-Florida line, beyond which it passes below the bed of the river. The thickness of this formation in Florida has not been determined.

The *Ocala formation* as developed in Florida consists for the most part of very pure limestone. Fossils are abundant, although many of the mollusks are preserved only as casts. The rock as a rule is granular and porous, although in places, by replacement, it has become close-grained and compact. Masses and layers of flint representing limestone replaced by silica are of frequent occurrence in this formation. Aside from the flint masses much of the rock consists of soft white limestone or shell marl. This formation is exposed to a limited extent on the Chipola River near Marianna, and also over a considerable area in central peninsular Florida. According to recent studies by Cushman the thickness of the formation is very moderate, in places not exceeding 40 or 50 feet.

OLIGOCENE

The Oligocene as limited by recent investigations includes in Florida only the Vicksburg, Chattahoochee, and Tampa formations. The Ocala formation, which had been placed by Dall and others in the Oligocene, has been placed in the Eocene upon the evidence of the molluscan fauna.[1] The Alum Bluff formation on the other hand formerly referred to the Upper Oligocene has been placed in recent years in the Miocene on the evidence of the vertebrates and invertebrates.[2]

The *Vicksburg formation* consists of limestones lithologically not unlike those of the Ocala formation. Exposures of the Vicksburg formation are found in Florida near Marianna and Chipley, in Jackson and Washington counties.

[1] G. Wythe Cooke, "The Age of the Ocala Limestone," *U.S. Geol. Surv., Prof. Paper 95*, 1915, pp. 107–17.

[2] E. H. Sellards, "Fossil Vertebrates from Florida; a New Miocene Fauna; New Pliocene Species; the Pleistocene Fauna," *Florida State Geol. Surv., 8th Ann. Rept.*, 1916, pp. 77–119, 5 pls. Carlotta J. Maury, "Santo Domingo Type Sections and Fossils," *Bull. Amer. Paleontology*, V, No. 30 (1917), Correlation table.

The Chattahoochee and Tampa formations, which apparently are in part at least contemporaneous in deposition, constitute the upper part of the Oligocene as developed in Florida. The *Chattahoochee formation* is well exposed on the Chattahoochee River from the Georgia-Florida state line to Rock Bluff, a distance of about twelve miles. Another considerable belt of exposures of this formation is found extending from the Ocklocknee River to or somewhat east of the Suwannee River, and from near the Georgia-Florida state line to the Gulf border. The formation as exposed on the Apalachicola River includes impure clayey limestones. A rather harder and perhaps more nearly pure limestone phase of the formation shows between the Ocklocknee and Suwannee rivers.

The *Tampa formation* is exposed on the Hillsboro River and on the Manatee River near Tampa. It is likewise a limestone varying in hardness and in purity. The thickness of the Oligocene in Florida is difficult to determine, since there are no surface exposures that afford a measurement of the combined thickness of the formations. The evidence from well records as to the thickness of these beds is at present too indefinite to be of service.

MIOCENE

The Miocene of Florida includes the Alum Bluff, Jacksonville, and Choctawhatchee formations. The *Alum Bluff formation*, formerly referred to the Oligocene, as already noted has been placed in the Miocene on the evidence of the vertebrate and invertebrate fossils. The materials of this formation include calcareous sands and sandstones varying to sandy limestones, calcareous clays, fuller's earth clays, and sands. The conditions under which the formation was deposited were evidently shallow water often in the presence of conflicting currents. This is especially true of the upper part of the formation in which cross-bedding is not uncommon. Fossil plants are found in this formation at the type locality at Alum Bluff. At the fuller's earth mines in Gadsden County there is found a limited although extremely interesting land vertebrate fauna associated with a shallow water invertebrate fauna. Farther to the west on the Choctawhatchee and Yellow rivers the formation

is more distinctly marine and contains an abundant marine invertebrate fauna. In the southern part of the state the deposits which are believed to represent the equivalent of the Alum Bluff formation are distinctly phosphatic. As there developed the formation consists chiefly of shell marl beds in which is included black, brown, and white phosphate pebble.

Deposits found on Black Creek in Clay County and referred to the *Jacksonville formation* are lithologically very similar to the Alum Bluff formation as developed in south Florida, and contain similar phosphate pebble.

The *Choctawhatchee formation* is later in age and overlies the Alum Bluff formation. It is chiefly a loosely cemented shell marl, formed in shallow water and often quite sandy. The surface outcrop of this formation occupies a narrow belt extending in a general east–west direction from west of the Choctawhatchee to somewhat east of the Ocklocknee rivers. In determining the thickness of the Miocene it is necessary to rely on well samples. At Jacksonville the Miocene apparently extends from near the surface (about 33 feet) to possibly as deep as 500 feet, giving for the formations of this period a thickness approximating 450 feet. Probably at least 400 feet of the section of the well at Fort Myers is likewise to be referred to the Miocene, while in the well at Okeechobee the Miocene apparently approximates 400 feet in thickness.

Phosphate in the Miocene.—Phosphate rock in considerable quantity appears for the first time in the Lower Miocene[1] (Alum Bluff formation), the phosphates of both the Alachua and Bone Valley formations having been derived from this formation; the hard rock chiefly by chemical, the land pebble phosphate chiefly by mechanical, segregation.[2] While the processes of concentration to

[1] In a well at Apopka, Florida, described in the *Twelfth Annual Report of the Florida Geological Survey*, Comanchean foraminifera have been identified by Cushman from limestones or marls with which is included a considerable quantity of pebble phosphate through a thickness of about 170 feet. Whether the phosphate belongs in this limestone or has fallen down from a higher level remains to be determined. At no other locality is pebble phosphate found in the Comanchean.

[2] E. H. Sellards, "Origin of the Hard Rock Phosphate Deposits of Florida," *Florida State Geol. Surv., 5th Ann. Rept.*, 1913, pp. 23–66; "The Pebble Phosphates of Florida," *ibid., 7th Ann. Rept.*, 1915, pp. 25–116.

workable deposits can be reasonably well followed there remains the problem of the origin of the phosphate in the Alum Bluff formation itself. The Eocene and Oligocene formations of peninsular Florida, are calcareous, some of them being very pure limestones. During the Lower Miocene, however, the conditions were changed to such an extent that very considerable quantities of land-derived sediments were carried into northern Florida. This change was perhaps gradual, as the lower part of the Alum Bluff formation is more calcareous than the upper part. Likewise the Alum Bluff formation of southern Florida is more calcareous than the same formation in northern Florida. At Alum Bluff, land plants are preserved in this formation, and in the fuller's earth mines are found land vertebrates. In south central Florida more or less shell marl is found in the Alum Bluff formation and in southern Florida a deposit of shell marl of great thickness was accumulated during this time. It seems probable that the phosphates of the Alum Bluff formation, from which in later times were formed the workable phosphate beds of Florida, accumulated through chemical or biochemical processes in the warm shallow seas in which were deposited the great marl beds of the formation.

PLIOCENE

Four formations in Florida, more or less well differentiated, are referred to the Pliocene. These are the Nashua and Caloosahatchee shell marls, and the Bone Valley and Alachua formations. The two first mentioned are marine formations. The *Nashua marls* are well developed on the St. Johns River in Putnam and Volusia counties. The *Caloosahatchee marls* find their typical development on the Caloosahatchee River. Both formations contain an abundant fauna of well-preserved invertebrates. The *Bone Valley formation* which contains the workable pebble phosphate deposits is well developed in Polk and Hillsboro counties. This formation is evidently of shallow-water origin and is in part at least estuarine. It represents material reaccumulated during Pliocene time, derived chiefly from the disintegration of the nearby Miocene deposits. The *Alachua formation* likewise represents a re-working of materials derived from the disintegration chiefly of the Miocene deposits and to some extent also of the older formations on which this formation

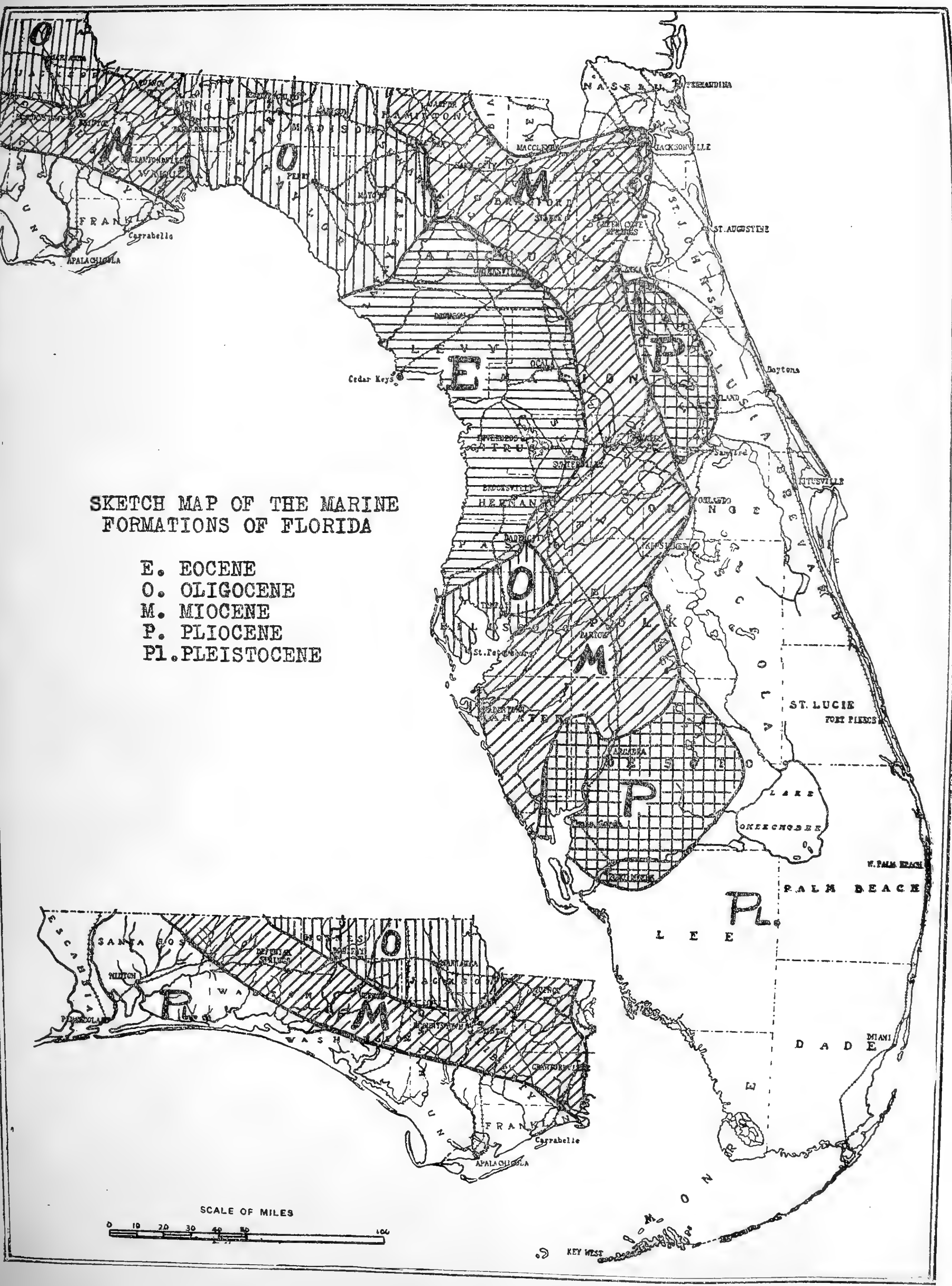
rests. The Alachua formation contains the workable deposits of hard rock phosphate. Both the Bone Valley and Alachua formations contain a vertebrate fauna on the basis of which the formations are referred to the Pliocene. The Bone Valley formation rarely exceeds 100 feet in thickness and as a rule is less. The Dunnellon formation likewise is usually less than 100 feet in thickness. Both the Nashua and Caloosahatchee formations so far as known are thin and may not exceed 50 or 100 feet.

PLEISTOCENE

The Pleistocene formations of Florida include river alluvial and marine deposits. The marine or chiefly marine Pleistocene deposits of the state have been described under the heading of Palm Beach limestone, Miami oölitic limestone, Key Largo limestone, Key West limestone, Lostmans River limestone, and Fort Thompson beds. The five first named are all of marine origin. The Fort Thompson beds include an alternation of fresh-water and marine deposits. All of these deposits are found in southern Florida and the interrelation of the several named units remains to be determined on more detailed stratigraphic work than has yet been done. Alluvial Pleistocene deposits are widely distributed over the state, especially in the stream valleys. In places these stream deposits contain vertebrate and invertebrate fossils.

GEOLOGIC SKETCH MAP

The sketch map (Plate II) shows in a general way the surface distribution of the Florida formations. Owing to the small scale of the map it has been necessary to combine the formations. It is also impracticable to show limited exposures, such for instance as the exposures of the Ocala Eocene on the Chipola River near Marianna, or of the Claiborne Eocene on the Choctawhatchee River near the Georgia-Florida state line. Outliers and remnants of some of the formations are omitted for the same reason. Thus over both the Eocene and the Oligocene of peninsular Florida are found remnants of the Lower Miocene, indicating probably the former extension of the Alum Bluff formation over the entire state. No attempt has been made to show the Alachua formation, which rests chiefly upon the Eocene of Alachua, Levy, Marion, and Citrus


SKETCH MAP OF THE MARINE
FORMATIONS OF FLORIDA
E. EOCENE
O. OLIGOCENE
M. MIOCENE
P. PLIOCENE
Pl. PLEISTOCENE
SCALE OF MILES
0 10 20 30 40 50 100
JACKSONVILLE
ST. AUGUSTINE
Daytona
Cedar Keys
St. Petersburg
ST. LUCIE
FORT PIERCE
LAKE
OKEECHOBEE
PALM BEACH
W. PALM BEACH
LEE
DADE
MIAMI
KEY WEST
Carrabelle
APALACHICOLA
FRANKLIN
TITUSVILLE
FERNANDINA
NASSAU
LEVY
E
O
M
P
PL

counties; nor the Bone Valley formation, which rests upon the Miocene of Polk and Hillsboro counties. The alluvial Pleistocene deposits are likewise omitted from the map, and also the limited exposures of Pliocene (?) on the St. Marys River.

STRUCTURAL CONDITIONS IN THE FLORIDIAN PLATEAU

THE RELATION OF THE FLORIDA PENINSULA TO THE COASTAL PLAIN

An unusual structural feature in coastal plains geology is the great Floridian plateau which, projecting from the mainland, separates the Atlantic Ocean from the Gulf of Mexico. The times of origin of this plateau may not be determinable, although it is now known to have been in existence and to have formed a large shallow-water area as early at least as the Lower Cretaceous or Comanchean period. Although affected by diastrophic agencies, including elevation and depression, this plateau has continued as a structural feature from the Comanchean or earlier to the present time.

For some years the Florida Geological Survey has been collecting well logs and well cuttings with a view to determining so far as practicable the structural conditions underlying peninsular Florida. This work has progressed slowly, although some data have now accumulated that have a very important bearing on this problem. Early in 1918 cuttings containing numerous foraminifera from a deep well then recently completed in Sumter County were sent to Dr. T. W. Vaughan, of the United States Geological Survey, by whom they were referred to Dr. J. A. Cushman. Dr. Cushman's identification of the foraminifera of these samples led to the very unexpected result that they indicated the presence of Comanchean (Lower Cretaceous) formations. Subsequently the foraminifera were identified by Dr. Cushman from the cuttings of about fifteen wells in Florida. In addition there are a number of other wells that from logs or samples give approximate data.

SKETCH MAP OF STRUCTURAL CONDITIONS IN FLORIDA

Upon the basis of all data available at this time there has been constructed a sketch map (Fig. 1) which represents approximately what is known of structural conditions in the peninsular section of

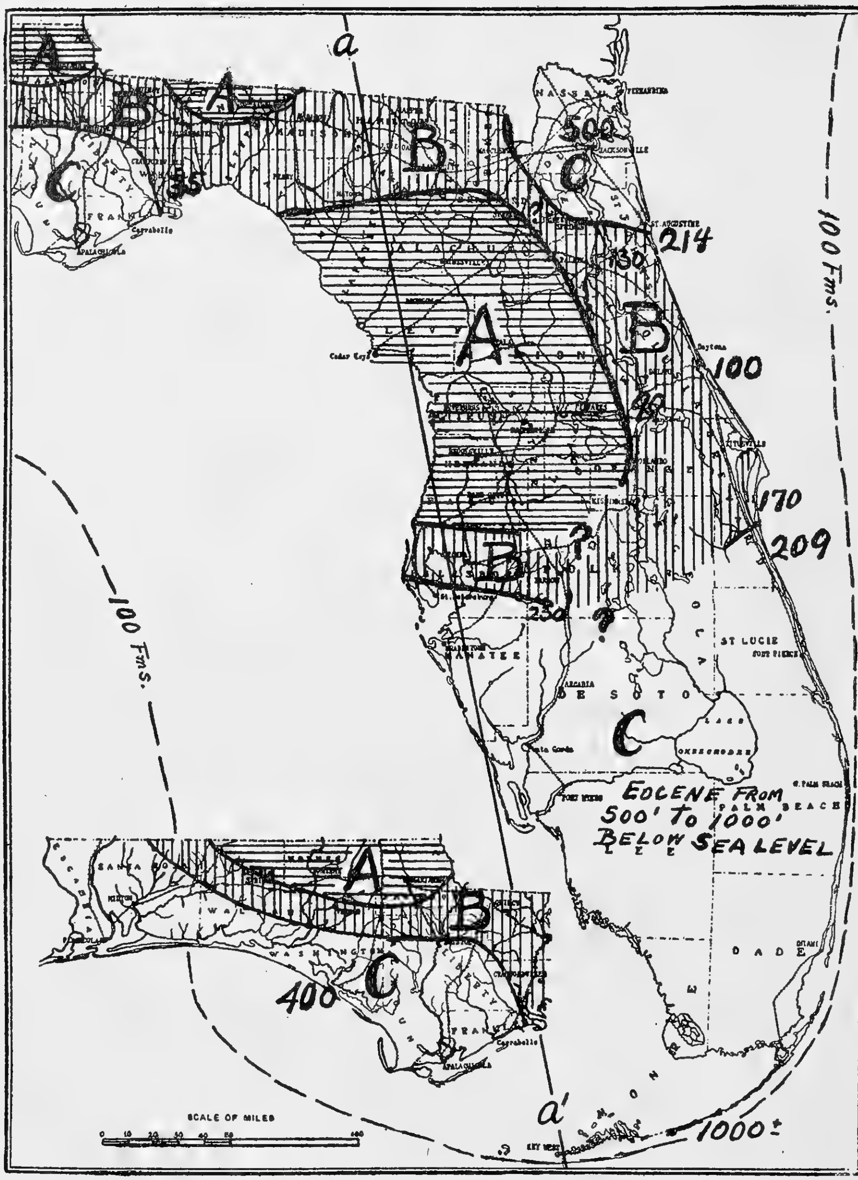


Fig. 1.—Sketch map to indicate general structural conditions in Florida: *A*, Belt of country in which the Eocene formations, when present, lie above sea-level, mostly from sea-level to as much as about 100 feet above; *B*, Eocene formations below sea-level; for the most part between 0 and 200 feet below. Doubtful territory for both belts *A* and *B* is indicated by a question mark; *C*, Eocene formations probably more than 200 feet below sea-level, varying from 200 feet to a maximum, so far as known, of about 1,000 feet in the southern part of the peninsula. Figures entered on the map record the approximate depth to the top surface of the Eocene, usually the Ocala formation. The margins of the Floridian land mass are approximately coincident with the 100-fathom contour, the location of which is indicated on the map. The axis of the land mass is approximately indicated by the line *a–a'*.

Florida. On this map there is indicated an area in the west central part of the peninsula, marked "A," in which the top of the Eocene limestones, when present, lies at or above sea-level. The data for placing the eastern margin of this area are very limited, and the boundaries are necessarily very roughly approximated. In the lake region of Clay County in particular it is possible that the Eocene may lie closer to the surface than is here indicated.

A second area, "B," is marked off on the map, in which generally speaking the top of the Eocene limestones appears to lie below sea-level, but at no place in excess of 200 feet below sea. These two areas, it will be noted, together make up a broad belt extending across and occupying all of the north central part of the peninsula from the Gulf to the Atlantic coasts. The data on which this belt is mapped is derived in part from surface exposures and in part from well records. The upper course of the Suwannee River in Florida is known to lie in a structurally low area, since in following the course of this stream it passes toward the Gulf to successively older formations. Since in Hamilton County the Alum Bluff Miocene is exposed at elevations not exceeding 75 feet above sea it is surmised that the Eocene will be found in this general area to lie below sea-level. From numerous wells drilled at Jacksonville it is known that the Eocene limestones there lie about 500 feet below sea-level. On the other hand, at Riverdale, on the St. Johns River about 35 miles south of Jacksonville, Eocene limestones are reached, as indicated by well cuttings, at about 211 feet below sea-level; while at St. Augustine the Ocala Eocene, on the authority of Dr. W. H. Dall, is placed at a depth of 224 feet from the surface or about 214 feet below sea-level.

In the well of Mr. Oliver Gibbs at Melbourne Beach, Eocene fossils were detected which, from the log of the well, appear to have come from the depth of 221 feet, the total depth of the well being 318 feet. At intermediate points between Melbourne and St. Augustine, on and near the coast the Eocene limestones lie, so far as determined, at depths between 100 or somewhat less and 200 feet below sea-level. This is true of wells at Cocoa, where Eocene fossils have been taken from a well the total depth of which does not exceed 190 feet; at New Smyrna, where the Eocene appears from

well samples to have been reached at a depth of 105 feet from the surface; at Daytona, where from well logs it would seem that the Eocene is somewhat shallower than at New Smyrna, lying apparently at less than 100 feet from the surface. The depth to the Eocene has been determined approximately at a few inland towns in this area. At Sanford, fossils of the Ocala formation have been identified by Cushman at a depth of 113 feet. The surface level at the old railway depot at Sanford is given as 20 feet above sea. The surface level at the well is not known but probably does not differ greatly from the level at the depot. The top surface of the Eocene therefore is probably somewhat less than 100 feet below sea-level. At Orange Mills the limestones, probably Eocene, have been reported at a depth of 130 feet, the surface elevation at this place being about 15 feet above sea-level. A slightly increased depth to these limestones is suggested by well records at Hastings.

In the well of the Palmetto Phosphate Company in Polk County the top of the Ocala is placed by Cushman at 360 feet. The surface elevation at Fort Meade is 130 feet above sea. Hence the actual level of the top surface of the Ocala formation is probably somewhat more than 200 feet below sea-level.

That part of the peninsula in which the Eocene formations so far as known lie at a depth of more than 200 feet below sea-level includes a small area in the northeastern part of the state and the whole of extreme southern Florida as well as a coastal belt west of the Apalachicola River. The depth at which the Eocene is known more or less definitely is indicated at several localities within this large area although the data is as yet very limited. There is in particular complete lack of information, as indicated by the use of the question mark on the map, in the southern part of the lake region, where the older formations may be expected to lie rather close to the surface.

ASYMMETRY OF THE FLORIDIAN PLATEAU

The actual position and extent of this plateau, as has been shown by Smith, Vaughan, and others,[1] is strikingly different to that which

[1] Eugene A. Smith, "On the Geology of Florida," *Am. Jour. Sci.* (3), XXI (1881), 292–309; T. Wayland Vaughan, "A Contribution to the Geologic History of the Floridian Plateau," Carnegie Institution of Washington, *Pub. No. 133*, 1910.

appears from the inspection of an ordinary map of the land areas. The 100-fathom contour may be taken as the approximate margin

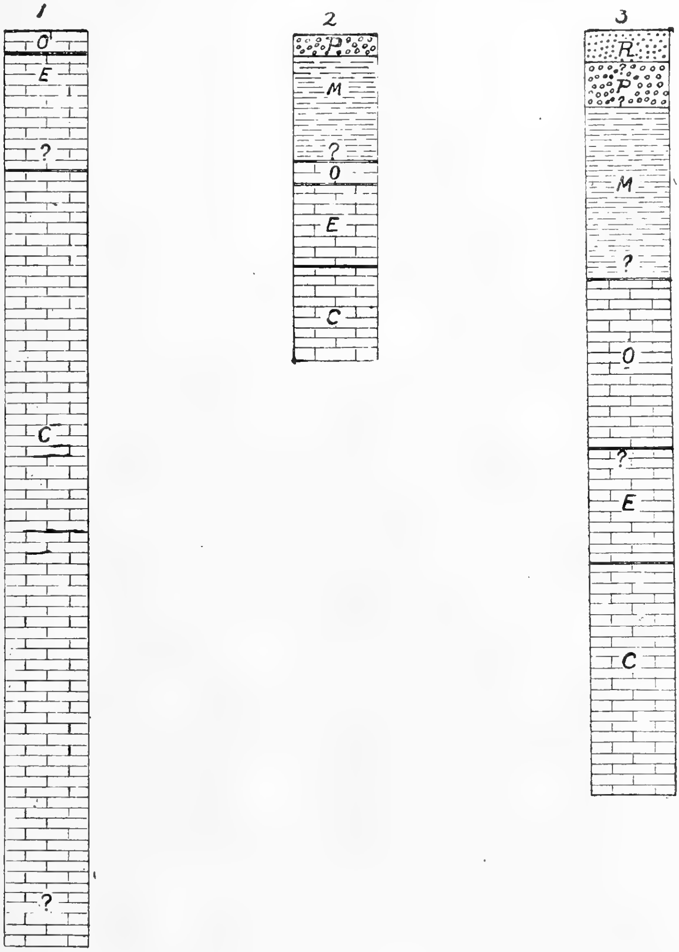


FIG. 2.—Thickness of formations as indicated by wells. Vertical scale, one inch equals 400 feet. No. 1, well in Wakulla County, eastern part of West Florida; No. 2, well of Palmetto Phosphate Company, Polk County, South Central Florida; No. 3, well of Florida East Coast Railway, on the Florida keys, Monroe County, South Florida.

of the plateau, since the slope to this line is for the most part gradual, while beyond this contour the slope is steep, and in places, especially toward the south end of the peninsula, is abrupt. Taking this

100-fathom contour as the margin it will be found that scarcely one-half of the plateau is above water, and that the greater part of that which is above water lies to the east of the north–south axis. With regard to elevation the plateau is therefore asymmetrical, the eastern half being higher, mostly above sea-level, than the western half, which is almost wholly submerged. This lack of symmetry is apparently due in particular to a tilting or warping of the peninsula toward the west, by which the coast of west Florida has been depressed as far south as Hernando County, while the east coast, including all of the southern tip of the peninsula, has been slightly elevated.

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VOLUME XXVII NUMBER 5

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

JULY-AUGUST 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, LONDON AND EDINBURGH
THE MARUZEN-KABUSHIKI-KAISHA, TOKYO, OSAKA, KYOTO, FUKUOKA, SENDAI
THE MISSION BOOK COMPANY, SHANGHAI

July-August 1919 Vol. XXVII, No. 5

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of The Journal of Geology, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Separates, if desired, must be ordered in advance of publication. Separates of leading articles will be printed as ordered, of which 50 (without covers) will be furnished *gratis*, the actual cost of the remainder (and covers, if desired) to be paid for by the author. The actual cost may vary, and will depend upon the amount of work in remaking the pages into forms, presswork, paper, binding, etc. Separates containing half-tones may be expected to cost somewhat more, the increase depending upon the number of cuts and the amount of work required upon them.

Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

Among articles to appear in the early numbers of *The Journal of Geology* are the following:

Pre-Cambrian Rocks of Southeast Newfoundland. By A. F. BUDDINGTON.

The Richardton Meteorite. By T. T. QUIRKE.

The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin. By W. H. TWENHOFEL.

A Laboratory Field Study of Cobble Abrasion. Preliminary Report. By C. K. WENTWORTH.

Crystallization-Differentiation in Igneous Magmas. By N. L. BOWEN.

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THE JOURNAL OF GEOLOGY

JULY-AUGUST 1919

INVESTIGATION VERSUS PROPAGANDISM

T. C. CHAMBERLIN
University of Chicago

The case of the ancient pottery-makers of Vero, Florida, seems really quite worthy of becoming a *cause célèbre.* It has already passed through two stages and is now well on in a third. The purpose of this paper is to urge that this third stage be closed at once by common consent and that the inquiry be pushed on into a fourth stage. The first stage embraced the discovery, the preliminary examinations, and the presentation of the case to the scientific public; the second covered some concerted field investigations by interested specialists and the publication of their results in symposia; in the third stage there has developed a tendency to lapse into isolated discussions with a trend toward controversy, as well as a trend toward premature propagandism. What should constitute the fourth stage may best be considered after such a brief review of what has been presented as shall make clear the status of the case at the close of the stages already past.

STAGE I. THE ANNOUNCEMENT AND PRELIMINARY PRESENTATION

The discovery, as is so often the case, was made incidentally in the progress of industrial work. The preliminary inquiries were of the usual type and the initial announcement was made to the

appropriate scientific jury through the venerable *American Journal of Science*. The subject was thus given a fitting introduction and a distinctly scientific aspect from the outset.

The presence of vertebrate fossils in deposits of a late age at Vero was learned as early as 1913. Fossil human remains were found in association with these in 1916. The first announcement by Dr. Elias H. Sellards, state geologist of Florida, was made in July, 1916. A supplementary statement in *Science* was made in October, 1916, and an official report in the *Eighth Annual Report of the Florida Geological Survey*. This stage presents an excellent example of the composite work that falls to the lot of state geologists and their associates, in which it is often necessary for a single inquirer or a small group to pass upon very complex phenomena whose ideal treatment calls for the co-operative work of many specialists.

The case as developed in this introductory stage.—Beneath the site of the finds the basal formation is a marine marl (coquina) commonly referred to a late Pleistocene age, though all or essentially all its fossils belong to living species. It spreads under the whole neighborhood, so far as present evidence goes, and forms an excellent basal datum plane. On this basal formation the retiring sea built sand flats and beach ridges, while the wind built dunes, the whole forming a low belt of finishing deposits. These lie along the margin of the present mainland, while across a sea inlet about a mile wide, lies a barrier reef now in process of building which forms the outermost coast line of the Atlantic. The low ridged belt on the edge of the mainland is known in the discussion as Vero Ridge.

After the withdrawal of the sea, surface wash deposits and fresh-water marls gathered to some extent in the shallow basins of these finishing formations. At the same time a small drainage system was established near Vero, now known as Van Valkenburg's Creek. The main stream channel was formed by the junction of two branches which in turn were sub-branched. All these features seem to have been determined mainly by the ridglets, swells, and hollows of the retiring sea deposits. The branchlets, however, reach back into a marshy tract west of the Vero Ridge. The united drainage from the north meets that from the south nearly head-on and the

two unite into a trunk stream flowing eastward to the sea about a mile away. The particular site of the human and vertebrate remains lies near the junction of the two branches.

Before the remains under debate could have been buried in the way in which they were found, the creek must have excavated a relatively broad flat with such low gradients as to permit aggradation. The average depth of the aggraded creek deposits is about six feet. They consist chiefly of washed sand and vegetal muck and other débris, with some fresh-water marl. They are thought by Dr. Sellards and most others to be divisible into two layers, a lower, No. 2, consisting of three to four feet of sand and muck, with fresh-water marl; while the upper, No. 3, consists more largely of muck and vegetal débris with a less proportion of sand, layer No. 1 being the marine marl below. The upper layer, No. 3, cuts here and there into No. 2, sometimes cutting entirely through it into the marine bed below.

In this first stage of inquiry, parts of two human skeletons were recognized, one of which was referred by Dr. Sellards to the lower creek deposit, No. 2, and the other to the upper creek deposit, No. 3. It was urged strongly in the initial papers that the scattered condition of the bones, as well as their other relations, shut out the probability, if not the possibility, of intrusive burial. On the other hand, it was urged that the human remains could not have been washed in from outside sources, or even transferred from the one layer to the other in any notable degree, because of the unworn state of some of the fossils and the fragile condition of others. A considerable number of the vertebrates found in the lower layer were identified as extinct forms; some of them had been usually referred to rather early stages of the Pleistocene. A smaller number of extinct vertebrates were found in the base of the upper layer, at about the same level as that of the human skeleton referred to that layer. The bones of the extinct vertebrates and of man were both found to be mineralized in much the same degree. With the human bones were found chipped stones, bone implements, and fragments of pottery.

On the basis of the evidence thus gathered the lower creek deposit, No. 2, was referred confidently ot the Pleistocene; the

upper layer was regarded also as probably Pleistocene, but some reservation was expressed respecting this.

STAGE II. CONCERTED INVESTIGATION AND CO-ORDINATE PUBLICATION

Closely following this introductory stage Dr. Sellards extended cordial invitations to various specialists to inspect the deposits and the material already gathered from them, and to join in further inquiry. Two field conferences followed. The earlier and larger was held in October, 1916, participated in by Dr. George G. MacCurdy, anthropologist of Yale University, who gave special attention to the archaeological evidence; Dr. Aleš Hrdlička, anthropologist of the U.S. National Museum, who gave special attention to the human bones; Dr. Thomas W. Vaughan, geologist in charge of the coastal plain investigations of the U.S. Geological Survey, who viewed the matter from the standpoint of the regional geologist; Dr. Oliver P. Hay, research associate of the Carnegie Institution in Vertebrate Paleontology, who studied in particular the evidence of the vertebrate bones; Dr. Rollin T. Chamberlin, associate professor of dynamic geology at the University of Chicago, who gave special attention to the physico-dynamical vestiges of the deposits and their import; Assistant Geologist Herman Gunter, of the Florida Geological Survey; Mr. Isaac M. Weills and Mr. Frank Ayers, citizens of Vero, who had taken an active interest in the discovery from the outset.

The results of this first conference were gathered into a symposium in the January-February, 1917, number of this *Journal*. The contributions were from Dr. Elias H. Sellards, embracing a report by Dr. Robert W. Shufeldt on the fossil birds (pp. 4–24); Dr. Rollin T. Chamberlin (pp. 25–39); Dr. Thomas W. Vaughan (pp. 40–42); Dr. Aleš Hrdlička, including a letter from Professor William H. Holmes (pp. 43–51); Dr. Oliver P. Hay (pp. 52–55); and Dr. George G. MacCurdy (pp. 56–62).

The second conference was held in March, 1917, Dr. Sellards again serving as host, participated in by Professor Edward W. Berry, paleobotanist of Johns Hopkins University, who gave especial attention to the testimony of the fossil plants; Dr. Rollin

T. Chamberlin, of Chicago, who returned for a more critical examination of certain features than was possible on the former visit; Assistant Geologist Herman Gunter, Mr. Isaac M. Weills, and Mr. Frank Ayers.

The results of the second field conference appeared in the October-November number of the same volume of this *Journal.* The contributions to this were from Dr. Elias H. Sellards (pp. 659–60), Dr. Edward W. Berry (pp. 661–66), and Dr. Rollin T. Chamberlin (pp. 667–83.)

The development of the case in connection with the two field conferences and the symposia.—It is aside from the purpose of this discussion to review these papers as personal contributions; we merely wish to trace the evolution of the case by contributions which represent different points of view and different methods of inquiry. We shall therefore merely try to bring out the most vital features of these papers as an additional résumé of the official composite work and as contributions from the standpoints of physico-dynamic inquiry, of vertebrate paleontology, of human osteology, of the human artifacts and industries, of fossil plants, and of other sources of evidence.

Preliminary to such outline, it may be helpful to remark that the Pleistocene age of the ancient men of Vero was pressed to the front as the specially vital question of the case at the outset. This specific question gave trend to the inquiry and to the contributions we are to sketch. Now, a dominating question of this kind inevitably forces the discussion to center, consciously or unconsciously, on the nominal or the conventional aspects of the case implied by the technical term Pleistocene, rather than on the strict realities involved in the case. The crux of the problem is thus made to hang more or less largely on technical terms. These in turn depend on the criteria that are accepted as guides in fixing the use of these terms. This grows naturally out of the history of attempts to show that man existed in America at certain early stages.

Three things are to be kept in mind in interpreting a discussion dominated by such a foremost feature: (1) the term Pleistocene is not used in precisely the same sense by all writers, (2) the criteria used in establishing the technical age are subject to challenge, and

(3) there are more vital questions than the simple Pleistocene or non-Pleistocene age of man in America.

Distinct foreshadowing of these points appeared in the conferences and symposia. The most significant of these was a rather distinct challenge of the trustworthiness of some of the criteria in so far as applicable to the case in hand, though heretofore regarded as good; modifications of the accepted criteria in certain vital aspects were suggested. This of course really means that they are not criteria at all, as used, and will become such only when properly revised. The stress of skepticism was thereby put on the criteria; and so the trustworthiness of these comes to the front as really the most vital feature of the case.

Now the criteria originally used in determining the divisions named Eocene, Miocene, Pliocene, Pleistocene, and Recent were made to rest on the numerical proportions of living species represented in the respective formations, viz.: in the Eocene, less than 5 per cent living species; in the Miocene, 20 to 40 per cent; in the Pliocene, more than half living species; and in the Pleistocene, about 95 per cent.[1] The species counted were chiefly, though not exclusively, marine. As the rates of change of marine forms differ from those of land forms and those of the land forms differ among themselves, this numerical basis was found unsatisfactory from the outset. As the real needs of the case developed, these original criteria were abandoned more or less completely and are now used only in a residual way in certain modified forms and in certain special situations. So far as the Pleistocene is concerned, the numerical paleontological criteria have been replaced to a large extent by physico-dynamic criteria drawn from the great ice invasions. This replacement constitutes a radical and significant departure. It is a part of the general movement to make the causal and world-wide agencies the basis of classification rather than their products, which vary with regional conditions.

For the close of the Pleistocene, in particular, the retreat of the continental glaciers from the plains of Europe and North America and the accompanying climatic effects are now the more generally accepted criteria. The substages of the Pleistocene are

[1] See Dana's *Manual of Geology*, fourth edition (1895), pp. 879–880.

marked off naturally by the successive ice invasions and retreats, because these very profoundly affected all the life in the middle and northern latitudes of the Eastern and Western hemispheres, while indirectly they greatly influenced the life-conditions in the more southerly latitudes.

Though these new physico-dynamic criteria do not afford very sharp lines of demarcation, they are in reality sharper than the paleontological criteria they have replaced. Changes of species are slower, and their interpretation more uncertain, than the changes in the great ice-sheets. It will help to show the real significance of the diverse interpretations of the Vero case if we here give a table of the relative dates of the several glacial stages compiled from estimates made by the more experienced students of glacial phenomena. Of course these are by no means final figures; they are held subject to very considerable changes as additional data are gathered; but they may be regarded as indicating tentatively the order of magnitude of the time-distribution of the glacial stages. We have derived from the compiled estimates what seem to us conservative minimum estimates.

ESTIMATED TIME-STAGES OF THE PLEISTOCENE PERIOD

	Compiled Estimate	Minimum Estimate
Close of Pleistocene, beginning of Recent	25,000 yrs. ago	20,000 yrs. ago
Climax of Late Wisconsin glacial stage..	40,000 " "	30,000 " "
Climax of Early Wisconsin glacial stage.	95,000 " "	60,000 " "
Middle of Peorian interglacial stage.....	135,000 " "	90,000 " "
Climax of Iowan glacial stage..........	180,000 " "	105,000 " "
Middle of Sangamon interglacial stage..	260,000 " "	155,000 " "
Climax of Illinoisan glacial stage.......	340,000 " "	190,000 " "
Middle of Yarmouth interglacial stage..	500,000 " "	275,000 " "
Climax of Kansan glacial stage.........	660,000 " "	330,000 " "
Middle of Aftonian interglacial stage....	900,000 " "	450,000 " "
Climax of Jerseyan glacial stage........	1,200,000 " "	540,000 " "

Maximum estimates should probably be double the compiled estimates in the later stages and more than double in the earlier stages.

Now, if we take the extreme ages to which the fossils at Vero have been referred by different members of the conferences, the

total range, using the minimum estimates of our table, is over four thousand centuries, and yet the deposits embrace a thickness of only six feet, the lowest layer of which was not deposited until some time after the last retreat of the sea from the mainland. This serves to indicate the stress the case has put on accepted criteria. With this aspect of the case in mind, let us note the essence of the several contributions to the symposia.

Further contributions from the viewpoint of the state geologist.—The two further contributions of Dr. Elias H. Sellards have the same import as his earlier papers already sketched. He, however, adds certain more declared statements that bear strongly on intrusive burial, on transfer by water and other natural agencies, and on original burial where now found.[1] Among these are the absence of whole skeletons, the infrequency of even complete individual bones, the scattered and imperfectly preserved state of the bones, their frequent and often sharply broken condition, together with evidence that "in the case both of the human and of the other vertebrates the bones were more or less disturbed after they had lost enough of their organic matter to become sufficiently brittle to break as they were moved about by water before reaching their final resting place."[1] "In the number of bones that have been obtained representing a single individual there is observed no important difference between the human and the other animals."[2]

The contribution from the physico-dynamic inquiry.—At the first conference an attempt was made by Dr. Rollin T. Chamberlin[3] to discriminate as closely as practicable what had been done at the successive formative stages, whether constructive or destructive, so as to give an analytical basis for the treatment of the special question under debate and for reconciling, so far as might be, the seemingly incompatible import of different criteria as then interpreted. The several episodes distinguished were as follows: the already well-recognized coquina marl, the datum base (Sellards' No. 1); the sand-capping over this and the formation of beach ridges and dunes; the gathering of fresh-water marl deposits, containing vertebrate remains, in the hollows of this low ridged

[1] Symposium 1, *Jour. Geol.*, XXV (January-February, 1917), 1, 22.

[2] *Ibid.*, p. 23.

[3] *Ibid.*, pp. 25–39.

tract; the formation back of the ridge—more or less contemporaneously with this—of a more extensive flat area with boggy tendencies, the most significant feature of which is an indurated black sand, from which pebbles ranging up to "cannon balls" were later derived and borne into the lower and upper fossil-bearing layers (Sellards' No. 2 and No. 3); the development of the drainage system of Van Valkenburg's Creek, partly in the one and partly in the other of these two upland formations; the excavation of the creek trench to a breadth and gradient suitable for the beginning of aggradation; the first stage of aggradation (Sellards' layer No. 2); and the second stage of aggradation (Sellards' No. 3).

On the basis of this analysis, a hypothesis was proposed which seemed to reconcile some of the apparently conflicting imports of the fossils in the lower and upper parts of the creek deposits. It postulated that the oldest extinct mammals came into the region as soon as it emerged from the sea, and were buried in the hollows and flats of the ridged tract, and more especially in the poorly drained, flattish area lying west of the Vero Ridge, whence at some time notably later they were carried into the creek deposits much as the black pebbles from the indurated sandstone of the same area were found to have been.

No time was available during the first conference after this hypothesis was formulated for testing it, and it was offered in this state in the first symposium as a hypothesis of reconciliation, and the earliest opportunity sought to put the hypothesis to the test. On his second visit, Dr. Chamberlin found the bog deposits back of the ridge essentially barren of fossils, suggesting conditions either inhospitable to life or unfavorable for its preservation. In his contribution to the second symposium the part of the hypothesis relating to the bog deposits was therefore frankly laid on the shelf; nor was the alternative phase which made the upland marl beds of other parts of the tract the source of the older fossils of the creek deposits further urged, because fossil-bearing deposits of this kind were not found in available situations, though they occur elsewhere. The part played by this stage between the retreat of the sea and the aggradation on the bottoms of Van Valkenburg's

Creek must of course yet be worked out and put in its place in the history of the formations at Vero.

On the shelving for the time being of this hypothesis of reconciliation an endeavor was made to detect such physical possibilities for faunal deployment as might be implied by the creek deposits themselves, thin as they are. The inquiry brought out the fact that the exposed sections of the creek filling showed distinctly more reworking in some portions than in others, together with the suggestive fact that where the layers were least irregular a fair line of distinction could be drawn between an upper and a lower portion, but that where there was most evidence of scour-and-fill the line of distinction between upper and lower layers was more obscure and at points quite uncertain. Discussion of the precise line of division between the layers, among the investigators while on the ground, brought out notable differences of opinion, and furthermore opinions were more or less changed as the inquiry went on. As the result of such changes of opinion, the dividing line was more often shifted downward than upward.[1] The effects of scour-and-fill in the more disturbed portions of the deposit were found very notable, and they were more pronounced in and near the critical horizon between the upper and lower deposits than at other levels. Scour holes were traced well down into the horizon assigned to the lower layer (No. 2), and even entirely through it into the marine marl below. It was observed that coquina shells had been carried up across the whole horizon of the lower layer and redeposited in the horizon of the upper layer. A careful excavation of a scour hole led to the successive placing of the dividing line between the layers at lower and lower levels, as the work went on, and in the end to the disclosure at the bottom of the hole of the carapaces of two turtles, apparently put there by the swirling water-hole action.

It was further observed that the portions of the creek deposits most marked by scour-and-fill action were the portions richest in human and extinct vertebrate remains, suggesting some causal connection between the scour-and-fill action and the accumulation of the relics.

[1] For details and illustrations see Symposium 2, *Jour. Geol.*, XXV (October-November, 1917), 673–82.

It appeared further that, while some of the relics were very fragile and could only be supposed to have been moved by very gentle processes—if moved at all after they reached their present condition—most of such fragile material belonged to the lower layer or to the more undisturbed portions of the upper layer, and so a correlation between the condition of the layers and the condition of their content was suggested.

The question of possible transference was further affected by finding relics of the same species as those to which the fragile specimens belonged in a condition that could easily stand transportation. There remained, however, in some parts of the deposit sufficient fragile material to indicate that it had not undergone more than the most gentle handling since the fragile state was acquired. Such cases, however, were largely in the lower layer and in the less irregular parts of the upper layer.

On the whole, this closer inspection of the deposits and their fossil content seemed to strengthen the presumption that some of the relics of the extinct animals were deposited in the lower layer when that layer was taking on the form it now bears and that these relics were not introduced by any subsequent process.

The import of these observations had the effect of throwing the stress of interpretation on the dividing tract between the two layers and on the upper layer. The termination of deposition of the upper part was definitely fixed at the year 1913, when the digging of the canal stopped the normal work of the creek. It appeared that such bones of extinct vertebrates as were found in this upper layer were much scattered; that their number was small relative to the whole number in the original skeletons, being commonly a few teeth, or a lower jaw, or one or two other bones, which did not seem to exclude some reworking but rather to imply it.[1]

In the light of this inquiry along physico-dynamic lines, the balance of evidence, taken all together, seemed to Dr. Chamberlin to favor the reference of such portions of the creek deposits as bear human relics to the later stage of filling, since all observers

[1] For specific details on these critical points see Symposium 2, *Jour. Geol.*, XXV (October-November, 1917), 676–82.

were agreed that the upper fill actually penetrates deep into the lower fill at several points, while the more critical examinations aided by excavations increased the evidence of such penetration.

Such seeming to be the import of the physical evidence, the testimony of the human bones and of the relics of human industries interpreted on their own grounds seemed to furnish the most available and precise criteria of the paleontological order that was available, and among the human relics the pottery seemed to give the most specific evidence. And so, adding the anthropologic and archaeologic testimony to the physico-dynamic evidence, Dr. Chamberlin concluded that the time of deposition of the upper layer belonged within the Recent Period, perhaps not dating back beyond the mid-Recent stage.

The contribution from vertebrate paleontology.—Dr. Oliver P. Hay identified the vertebrate fauna found in the lower part of the creek deposits at Vero as

> essentially that which is found in the Aftonian interglacial beds of Iowa and in the Equus beds of the Plains. From the latter, this fauna may be followed into Texas, thence eastward into Florida and South Carolina. Of this fauna, two species of elephants, the common mastodon, *Megalonyx*, and the giant beaver continued on until after the Wisconsin glacial stage. Other species, the saber-toothed tigers, *Equus complicatus*, the tapirs, most of the extinct bisons, and *Mylodon* probably disappeared before the Wisconsin glacial stage. In the earlier Pleistocene deposits only are found *Elephas imperator*, camels, several species of horses, and many edentates. At Vero have been found three species of horses, at least four edentates (including *Mylodon*), and a camel. *Chlamytherium* was originally found on Peace Creek in deposits which were then supposed to be Pliocene. In the same deposits was found a jaw containing a tooth of an elephant which is quite likely *E. imperator*. This species has not yet been found in No. 2 at Vero, but about three miles west of the place Sellards found a lower jaw which belongs probably to this species. It is known from Dallas County, Alabama, and from Charleston, South Carolina. [Dr. Hay regards it and camel remains as particularly indicative of the Aftonian fauna.] It is possible that this fauna continued on for another stage or two without great change, but by the time of the Illinoisian drift it had become essentially modified.[1]

Dr. Hay regarded the vertebrate fauna of deposit No. 2 as primary, thus making the deposition of the beds as now seen also Pleistocene in age.

[1] Symposium 1, *Jour. Geol.*, XXV (1917), 54–55.

No place was discovered from which the included bones and teeth might have been washed in, nor do they in general have the appearance of transported fossils. These bony remains are in what may be regarded as a normal condition; as when, in a little valley furnishing food and drink and shade, herbivorous and carnivorous species had resorted and perished there for thousands of years. In a normal way their bones have almost all fallen into dust. Some, buried under somewhat favorable conditions, endured longer, but softened and were trampled into fragments by succeeding generations of elephants, mastodons, horses, bisons, huge ground sloths, and smaller forms. Only the most favored and protected bones and teeth have endured to the present, mostly scattered, but sometimes remaining associated with others of the same skeleton.[1]

Dr. Hay regarded the lower part, at least, of No. 3 as also Pleistocene.

This deposit is somewhat more difficult to work for fossils, but it has furnished almost all the forms that are found in No. 2. It is not improbable that some bones and teeth were redeposited from the lower stratum, but not, I think, any considerable or essential portion of them.[2]

In the *Ninth Annual Report of the Florida Geological Survey*,[3] Dr. Hay treats more fully the vertebrate remains from the beds in question, mostly those of the upper layer, and reaffirms his belief not only that the fossils represent an early or middle Pleistocene fauna, but that the deposits in which they are now embedded are early and middle Pleistocene in age also.[4]

Dr. Robert W. Shufeldt described the fossil bird bones but does not discuss their bearing on the age of the deposits further than to indicate that some of the species are extinct.[5]

Contribution from the standpoint of paleobotany.—In his report on the fossil plants, Dr. Edward W. Berry says that "plant remains in the form of laminae of impure peat or scattered fruits, chiefly acorns, are present from the bottom to the top of the deposits overlying the shell marl which forms the base of the section. The lower sands (designated No. 2 by Sellards) have yielded

[1] Symposium 1, *Jour. Geol.*, XXV (1917), 52.

[2] *Ibid.*

[3] Pp. 43–68.

[4] *Ninth Annual Rept., Florida Geol. Survey*, p. 67.

[5] Symposium 1, *Jour. Geol.*, XXV (1917), 18–19; *Ninth Annual Rept., Florida Geol. Survey*, 1917, pp. 35–42.

no leaves and but few acorns, but the upper bed (designated No. 3 by Sellards) contains many leaf layers alternating with sand laminae."[1]

Recent and extinct mammalian and other bones occur in both layers, and human remains are also found in both beds. After a thorough study of the local sections and the paleontologic evidence I am convinced that there is no hiatus between beds Nos. 2 and 3 and that there is no great difference in age from the bottom to the top of the section, although it records changing physical conditions and necessarily becomes gradually more and more recent as the top of the section is approached. The lower sand marks the recession of the sea in which the underlying shell marl was formed. The upper beds (No. 3) mark successive seasonal layers of valley filling in the narrow valley of a small stream. This stream was apparently always small, and the marvelous abundance of fossils at this one point seems to be due to a bar or sink-hole or similar cache formed near the junction of the two lateral branches which united near this point to form the main stream. The determinable plants are represented almost exclusively by fruits or seeds, as the leaves, with the exception of the coriaceous oaks, which are abundant, were too thoroughly decayed before they were buried to retain their identity.[2]

After a summary grouping and discussion of species, Dr. Berry concludes:

In my judgment and in the ordinary acceptance of that term this flora is unquestionably of late Pleistocene age.

Regarding its bearing on the interesting problem of the age of the human and associated mammalian and other remains at Vero, my study of the locality furnishes the following somewhat categorical conclusions. The underlying shell marl which forms a definite and undisputed datum plane, is late Pleistocene in age. Its species all exist in near-by waters at the present time. . . . . It follows that the vertebrate remains which are so numerous at Vero cannot possibly be of Middle or Early Pleistocene age unless they are regarded as having been reworked from older deposits, and I cannot conceive that this was possible, nor do the vertebrate paleontologists who have examined the deposits consider that such was the case. . . . . Nothing is more reasonable than to suppose that the larger elements in the Middle Pleistocene fauna of more northern areas should have lingered for thousands of years in this more genial southern clime until the presence of man in considerable numbers and the changing climate, as is attested by the fossil plants, should have brought about the extinction of a large percentage of the fauna. The fauna itself confirms the rather limited data furnished by the fossil flora of this change in climate,

[1] Symposium 2, *Jour. Geol.*, XXV (October-November 1917), 661.

[2] *Ninth Annual Rept., Florida Geol. Survey*, 1917, pp. 19–20.

since it indicates a more mesophytic habitat than exists today in the vicinity of Vero. . . . . I therefore see no reason to doubt that relatively modern men were contemporaneous with this partially extinct fauna of Middle Pleistocene aspect which survived in Florida to the late Pleistocene. With regard to the exact age of the Vero deposits there are, it seems to me, but two alternatives, and these apply equally and are in large part derived from a study of the physiography and the faunas and floras of the corresponding topographic forms in the other states of the Coastal Plain. These alternatives are that they are about the same age as the Peorian interglacial deposits of the Mississippi Valley or are immediately post-Wisconsin and correspond with what the Scandinavian geologists have named Litorina time.[1]

Contribution from the viewpoint of the fossil beetles.—Recently a contribution relative to the fossil beetles has been made by H. F. Wickham, which is given a place here. The following is the author's summary:

Two conclusions seem to be warranted after a study of the beetle fragments. The first is that there is nothing to indicate any particular difference in climatic conditions in Florida then and now, since the assemblage of genera is the same as one might expect to find in a stream valley there today. The nearest relatives of the species are still characteristic members of the Floridian fauna and many of them are apparently identical. Second, it seems evident that there has been some change in minor characters of sculpture, since it is not possible to match certain of the fossils exactly with modern forms. In view of the fact that other researches indicate that insect evolution has been extremely slow, so that many species, even as old as the Tertiaries, are rather difficult to discriminate from their modern allies, no more marked divergence would be anticipated.[2]

Contribution from the viewpoint of regional geology.—Obviously the formations that occupy the adjacent coastal region and reach back to the glacial deposits have a vital bearing on the interpretation of the Vero deposits, and so the problem of interpretation as seen from the standpoint of the geologist in charge of the coastal plain investigations of the U.S. Geological Survey, Dr. Thomas W. Vaughan, constitutes a contribution on a distinct basis. The following is the essence of his conclusions: "The occurrence of artifacts and human bones in association with Pleistocene fossils does not prove the Pleistocene age of man," since previous investigations have shown that human artifacts and bones, by many

[1] *Ninth Annual Rept., Florida Geol. Survey,* 1917, pp. 31–33.

[2] *Amer. Jour. Science,* May, 1919, p. 355.

agencies, natural and artificial, have been carried below the surface and become imbedded in unconsolidated deposits. "The only indisputable geologic proof of the Pleistocene age of man must consist in finding a continuous undisturbed bed or layer of demonstrable Pleistocene age above the human remains."[1] In view of the questions that are still undetermined, he advises suspension of judgment for the present.

Contribution from the testimony of the human bones.—Dr. Aleš Hrdlička, after describing critically the human bones, expresses the unreserved opinion that they do not differ in any essential respect from those of the modern Florida Indians.[2] He argues in favor of the human burial of the remains, but this, of course, is geological rather than anthropological and is only incidental to his testimony as an expert student of the human skeletons themselves. He reaches the conclusion that the human bones found at Vero may well be prehistoric, and date from the early part of the occupation of the Florida peninsula by the Indians, but that no proof is furnished by the circumstances of the find, or by the human bones themselves, which would relegate the latter to an antiquity comparable with that of the extinct fossil remains with which they are associated.

Contribution from the viewpoint of the human artifacts.—In a note inclosed in Dr. Hrdlička's paper, Dr. William H. Holmes reports on twenty pieces of pottery collected near the human bones, that

> they represent moderately small, undecorated vessels, apparently simple bowls such as were in common use among the Indian tribes of Florida. Compared with corresponding plain vessel fragments from Florida sand mounds and from occupied sites generally, no significant distinctions can be made; in material, thickness of walls, finish of rim, surface finish, color, state of preservation, and size and shape of vessels represented, all are identical. There thus appears not the least ground in the evidence of the specimens themselves for the assumption that the Vero pottery pertains to any other than Columbian and immediately pre-Columbian time.[3]

The more comprehensive contribution from the archaeological point of view was made by Dr. George G. MacCurdy, who took

[1] Symposium 1, *Jour. Geol.*, XXV (1917), 41. [2] *Ibid.*, p. 50.

[3] *Ibid.*, 51.

part in the first conference and symposium. His discussion covers the import of the flint spalls and implements, the bone implements and the pottery. In the course of critical descriptions and observations on these he notes that two of the spalls are identical in material and might well have been chipped from the same flint block. One was found in bed No. 2 and the other in bed No. 3, which he regards as significant and raises the question whether both might not have come from the upper bed through the agency of growing roots or burrowing animals. The spalls were never retouched and were evidently chipped from the parent block near where they were found. As the parent rock is not found in place nearer than the Ocala formation, one hundred miles distant, he thinks the transportation was by human agency. A typical arrowhead of flint with barbs and stem implies the end sought in the chipping and the state of the industry.

To summarize the archaeological evidences of man's antiquity at Vero, one can say that the pottery, bone implements, including fishhooks, boneheads, and flint arrowheads from stratum No. 3 and from the surface of contact between it and the stratum below, all point to a period that might well have continued down to the close of the prehistoric period in Florida. This is also true of the human skeletal remains from the third stratum. On the other hand, of the 25 mammalian species from the second stratum as listed by Dr. Sellards, ten, including *Elephas columbi*, *Mammut americanum*, *Equus leidyi* (?) and *Tapirus haysii* (?), recur in stratum No. 3. Assuming that the stratigraphy is not misleading, the conclusion is either that this particular phase of the Neolithic period in America dates back farther than many had supposed, or else that certain fossil mammals continued to live on in Florida until a comparatively recent date.

The chief interest centers in the second stratum. From it no undoubted stone implements have thus far been reported. Although probably produced through human agency, the flint spalls from this deposit do not differ from those in the deposit above, in one case there being absolute identity of material. While a greater number of bone objects have been found in the third deposit than in the second, bone points of the same type occur in both; neither do these seem to differ as to their chemical state. Potsherds, fairly frequent in stratum No. 3, have not yet been reported from the stratum below. Of the human skeletal remains there does not seem to be any appreciable differentiation between those from the second and those from the third stratum.

There are to be noted then the absence of well-defined stone artifacts and of pottery from the second deposit; the presence of both in the third; the similarity

of the flint chips from the two deposits; the similarity of the bone points in both deposits; and the greater number and variety of bone artifacts, including ornaments in the third deposit. But for the similarity of the flint chips and the bone points, the cultural evidence is very much as one might have been led to expect, assuming of course that the stratigraphy is unmixed and that all specimens have been found *in situ*. On the other hand, in the absence of stratigraphy as a guide, of all the human and cultural remains reported from stratum No. 2, none would seem out of place in stratum No. 3.

. . . . The presence of plant stems, acorn cups, and pieces of wood in the second stratum, although by no means so abundant as in the third stratum, nevertheless give to it an aspect of comparative newness. Some of the leaves in the muck at the base of the third stratum look as if they might have been buried only a few years ago.

From observations made on the spot and from a study of specimens submitted, the writer is of the opinion that for the most part the human skeletal remains, flint chips, and artifacts probably found their way to this meeting-place of waters through the same agencies as did the various animal and plant remains, and that there has been more or less dove-tailing of the two deposits, because of the peculiar location of the site at the junction of two streams coming from opposite directions. If these premises be true, it would be hazardous to attribute any great antiquity to even the oldest human and cultural remains from Vero. It would be more logical to assume that some of the extinct forms found in the second stratum are perhaps derived from an older deposit; that others lived on in that southern clime longer than has hitherto been supposed, and that the presence of the Indian hunter had much to do with the final ringing down of the curtain on the drama of their ultimate extinction.[1]

It will be seen from these summaries that no consensus of opinion was reached or even approached by the several special students who attacked the problem from their own special points of view. The problem, however, was opened up broadly and the lines of profitable future work fairly well indicated, though not specifically stated. The most radical feature disclosed is the very different degrees of confidence reposed in different criteria. As we have already remarked, the really vital question raised by the Vero case is the value of the various criteria that have been in use and continue to be used.

Whatever else may be said, the outcome offered no warrant for the public propagation of any decision or consensus, pro or con, respecting the Pleistocene age of the ancient Vero man.

[1] Symposium 1, *Jour. Geol.*, XXV (1917), 60–62.

The several views relative to the age of the Vero man may be summarized as follows:

From the viewpoint of the State Geologist—Pleistocene.
From the viewpoint of regional geology—opinion withheld.
From the viewpoint of physico-dynamic geology—Mid-Recent.
From the viewpoint of archaeology—Recent.
From the viewpoint of anthropology—Recent.
From the viewpoint of vertebrate paleontology—Early or Middle Pleistocene.
From the viewpoint of paleobotany—Late Pleistocene.
From the viewpoint of invertebrate paleontology— ?

STAGE III. A TREND TOWARD ANTAGONISM AND PROPAGANDISM

The preceding co-operative stage was wholesome and fruitful in a gratifying degree, however indecisive. It is less gratifying to note that some signs of a lapse into polemics have recently manifested themselves. While the utmost independence and the highest critical spirit are eminently wholesome, criticisms from personal points of view that take such a form as to place an opposing view at a disadvantage, either from inadequacy or inaccuracy of statement, do not make for wholesome progress. They are not likely to be altogether fair—however well intended—either to readers or to those criticized. If something in that line is regarded as necessary, it is much better given the form of a joint discussion, preferably with exchange of manuscript beforehand. Such a discussion puts both sides before the reader at the same time and on equal footing. If it is felt that an attack must be made, let it be arranged that the defense go with the attack in the spirit of ancient chivalrous combats and in the not less chivalrous spirit of the most approved form of modern polemics.

Partly in association with more or less polemical reviews and partly independent of them, there has appeared also some tendency to propagate preferred views as though they were determinate while yet about half those who have taken part in the inquiry dissent from such views. Unless the fact of such dissent is duly impressed on the reader, he is placed under the disadvantage of partisan influence, and if he is keenly alive to his rights, he is likely to resent this. The varied opinions cited above seem quite clearly

to imply that the time for propagating the Pleistocene or the non-Pleistocene age of man in Florida has not yet come.

But let us pass lightly by this diversive stage and consider whether a rejuvenated effort of the co-operative order may not be made the most worthy successor of the already fruitful second stage.

STAGE IV. FURTHER EFFORTS AT RECONCILIATION AND REVISION

What is the most laudable line of future effort in the light of the disclosures of the preceding conferences? Is it not obviously a concerted effort to evaluate the criteria brought into service, to revise them if found necessary, and to find in an analysis of the case the means of reconciliation of the divergent views? Certainly the true end of endeavor is a concurrent interpretation. To this end should not each advocate stand ready to reshape his view so that it shall be reconcilable, so far as possible, with the evidences that seem to favor some opposing view? We may be sure that Dame Nature has proceeded rationally in the operations at Vero, as everywhere else, and that there really is complete harmony and consistency in the evidences presented.

We beg to make a few observations by way of suggesting further studies in the interest of such revision and reconciliation, but let it be clearly understood that these are but suggestions to deploy the case for additional investigation; they are not proposed solutions.

a) *Suggestions relative to the creek deposits themselves.*—Present processes are fairly clear and quite demonstrable. Recent processes should naturally be next most clear and most demonstrable. May it not be well then to change the order of inquiry by starting where the evidence is best and try to determine first what amount of aggradational work may reasonably be assigned Van Valkenburg's Creek during the Recent Period? The probable minimum length of this, according to the tentative scale given on a previous page, is two hundred centuries. By analyzing its formative processes, it should be possible to reach some approximate notion of the nature of the recent work of Van Valkenburg's Creek and perhaps of its time-relations. The results projected backward

from 1913—when the digging of the canal interrupted the normal work of the creek—for two hundred centuries should give a fairly firm first step in interpreting the actual six feet of creek deposits, if these are to be interpreted as simple aggradational accretions that have escaped reworking. If, on the other hand, reworking has seriously influenced the case, some of the criteria thus far much insisted upon may be brought into question.

Such an inquiry might start from two questions: (1) What is the *normal* thickness of vegetal muck and sand that might reasonably be expected to accumulate in such a situation during the Recent Period? (2) What is the *minimum* amount that can reasonably be thought to satisfy the demands of the case? The first question looks simply to the most rational estimate of work done; the second is influenced by a desire to leave as much as possible of the six feet of the actual deposit for assignment to earlier stages to help reconcile the shallow depth of the deposit with the faunal evidences that imply a great lapse of time. This finds its justification in the fact that a heavy stress is put on interpretation somewhere, and it is in the line of reconciliation for each advocate of a particular view to leave as much leeway as he can consistently for the accommodation of conflicting views. This in the end may be found to be the only way to save his own criteria from serious challenge.

To realize the grave nature of the stress which the case presents in only one of several particulars, let us for the moment suppose that the rate of aggradation on the flood-plain of the creek is no more than one inch per century; the total aggradation of the flood-plain in the two hundred centuries assigned the Recent Period would be more than twice the whole six feet actually shown in the creek sections. The supposition is of course merely illustrative.

Preliminary to any true estimate of an actual deposit of this type, it is necessary to inquire how a creek does its aggrading work on a low gradient plain of its own formation when controlled by a sea-level near at hand. Whatever else is involved—and there is much that cannot be noted here—two quite different classes of work are involved: (1) that done upon the flood-plain which occupies all the creek bottoms not at the time included in the creek

channel; (2) that done in the more limited tract of the stream channel itself. It is essential to note the normal differences between these two forms of deposit and their working relations to one another.

(1) The flood-plain deposits are formed of the residue of whatever grows upon the flood-plain, or may fall upon it in any way, or may be blown upon it by the winds, or may be mired in it when wet and soft, together with whatever may be washed upon it by the stream at the times of freshet or flood. When first spread upon the bottom, the deposits of freshet and flood stages are usually stratified, but they are quite sure to suffer serious disruption by the growth of plants, the tread of animals, and various other surface agencies, so that they very commonly lose their original structure. On bottoms of low gradient in a sandy tract flood-plain deposits are thus likely to be a heterogeneous mixture of vegetal and earthy muck combined with more or less sand, and to embrace as incidentals the hard parts of whatever lives and leaves its relics on the flat surface.

(2) The channel deposits, on the other hand, are usually formed mainly of the normal products carried by the stream along its bottom, notably sand and pebbles, but these are quite sure to be more or less mixed with derivatives from the flood-plain deposits that form the banks of the stream. More or less constantly these muck banks are being undercut and caused to slide into the channel where they are then more or less reworked by the stream. Usually the muck masses are gradually disintegrated and washed onward by the stream, but they may be buried bodily in its sands, thus carrying into these sands whatever the muck masses happen to contain. This content is likely to retain whatever condition it happened to have when in the muck bank.

In addition to these normal processes the stream, at appropriate points here and there, is also engaged in the work of scour-and-fill. This accidents the results and adds its special features to the products of the more uniform channel work.

Now this tripartite work is pre-eminently a mixing process; at the same time it is an assorting process. Each of these two processes is likely to be carried to varying degrees in the mul-

titude of individual cases involved; the mixed product thus commonly shows a wide range of variation. In part the mixing may be very gentle and the hard parts in the muck may show very slight abrasion. The slide of the muck banks into the bed of the creek is often one of the gentlest of moving processes, for the muck lubricates and cushions the sliding mass. The matter enveloped in the muck, however weak it may be, is easily slipped along in its cushion without appreciable strain or abrasion. Muck balls may even be formed and rolled notable distances, carrying in their protecting embrace structures of any degree of fragility until burial shall finally fix them in the stream sands or disintegration shall free them for a cleaner burial in the same sands. The typical channel material in the stricter sense, that is, the material which has been rolled along the stream bed for considerable distances, perhaps from sources beyond the aggradational tract, is normally much more worn, whether it be rock or bones. The several parts of the creek deposit are thus likely to show the effects of very different experiences. Only a critical study of each individual relic is usually sufficient to disclose its special history. Normally there is a very wide variation of conditions ranging from relics that remain almost intact to those which are very much abraded.

Now it is the normal habit of a stream that meanders on a plain of its own formation to shift its channel gradually downstream by undercutting or eroding its banks preponderantly on the down-stream side. In the course of time the stream thus slowly creeps over its whole flood-plain, and in so doing cuts away and reworks a large part of the flood-plain deposit. As the meanders thus slowly shear their way over new ground, new flood-plain deposits are formed on the ground abandoned by them; thus the flood-plain is rebuilt behind the shearing meander and made ready to be cut away again when the next meander reaches it in its progress down-stream.

Now, as already noted, this shearing process is attended almost inevitably by the special supplementary work of scour-and-fill which bores its holes below the common channel-level at the points of specially forceful or turbulent action. This is particu-

larly characteristic of streams subject to great variations of vigor, as for example streams in regions of alternating dry and wet seasons, as in the Vero case, especially when heavy rains are frequent and even typhoons are occasional. This scour-and-fill action is a special mixing process superposed on the more general ones already sketched.

Now if, in the case in hand, only a foot or so be allowed for the flood-plain deposits in process of growth, and only a foot or so for the normal channel-work, and only a foot or so below that for the deeper scour holes here and there, the vertical range of this active formative and reworking process is too great to be neglected when there are only six feet of deposits altogether to be dealt with. It must be kept in mind that this working combination, now at the top, has in the process of forming the six-foot deposit gradually worked up from the bottom, leaving some portion of its base at successive stages to help build up the lower part of the six feet. This lower part is thus an accumulation of residues from the working combination.

It is therefore necessary to distinguish between the working group at the top—which in the case in hand ceased its formative process in 1913—and the succession of residual deposits below it, these being merely the truncated bases of the formative deposits which the successive meander-shears have left behind. The group in process of formation at the top belongs not so much to the Recent Period as to the current working stage. Setting this aside as merely the record of the work in progress when suspended, how much more is to be added from the rest of the six feet below to make up a reasonable record of the past two hundred centuries, more or less, which, according to our tentative scale, constitute the Recent Period? Will anything less than the two or three feet of the upper layer, No. 3, suffice? Indeed, is that enough?

This method of proceeding from the known to the unknown seems eminently sound and helpful up to this point; here it encounters difficulties and these show its limitations. Theoretically, the several basal accretions left by the successive meander-shears may (1) have some notable thickness, (2) or very little thickness, or (3) even a minus thickness, i.e., there may be loss

of previous gains by the shearing away of more than has been built up since the last shear. Besides this, the time between meander-shears is also more or less uncertain. Just what the actual amount of accretion was in each intershear interval, in the case in hand, can only be determined by an inspection of the accretion layers themselves, if indeed their condition permits this. Even that may not suffice for a positive determination, but it is worthy of trial. Herein lies one of the calls for further investigation before anything purporting to be a final conclusion is put forth.

The method of inquiry here suggested, in spite of its limitations, clearly has these good points: (1) It begins with what is best known and forces a recognition of the formative group of deposits at the surface; (2) it suggests a specific kind of examination of the beds below this working group for specific data; (3) it invites a very critical study of the effects of transfer from one formative deposit to another under conditions whose possibilities are both great and highly varied; (4) it is well suited to throw light on the significant fact that, while only a very small fraction of the total number of bones belonging to any individual skeleton have been found in the deposits in question, implying that the great majority have somehow been carried away or otherwise disposed of, some of these are yet not necessarily much worn; (5) it is well suited to explain why much-worn material and little-worn material occur together; and (6) it makes altogether natural a gradation from the older to the younger content, attended with intermixture.

If the normal mode of formation of creek deposits were the only consideration to be weighed in the matter, the six feet of the deposit might perhaps be so handled in interpretation as to plausibly represent the stream aggradation during all the time between the Aftonian interglacial epoch and the present, though that would seem to be putting a very heavy strain on the probabilities; at least the deposits might not yield any demonstrative evidence to the contrary. So far as it goes, therefore, the method gives a possible basis of reconciliation between the import of the fossils in the basal part of the six feet, interpreted as very

old relatively, and the obvious recency of the upper part. The method is certainly helpful in explaining the crowding into close positional association faunas heretofore regarded as very different in age. To that extent it gives relief to one of the most declared phases of stress that make the case a really notable one.

The one feature in this mode of analysis and interpretation that may not be acceptable to some of the interested students of the case lies in the fact that it not only permits but postulates much transfer from a state of first burial in the flood-plain muck to a state of later burial in the channel sands, and to still further rehandling by the scour-and-fill process. However, this is not that phase of transfer that has been most under discussion in the history of the case. The interpretation suggested does not necessarily involve any transfer from an independent deposit somewhere else to the creek deposits. It is purely negative on this question, which is left to be decided pro or con by its own class of evidence.

A possible episode in the history of the Van Valkenburg's Creek deposits must be suggested briefly to meet one other phase of the deposits. There are specific grounds for thinking that the gradient of the creek may have been steepened, for a time, at some period between that of its early adjustment to the sea as it retired and its adjustment that now obtains at about the same level. Some of the streams, harbors, and inlets in the region seem to occupy drowned valleys, and this has been held by Shaler, Matson, and others to imply that a lower relative level of the sea, to the extent of twenty or thirty feet, obtained for a time. Such relative lowering of the sea-level, if it occurred, would naturally have caused Van Valkenburg's Creek to sink its channel—attended perhaps by a flood-plain of greater or less extent also—into the previous aggradation plain. As the sea-level again arose to its present position, the sunken trench should have been refilled until aggradation would be resumed on the level of the old plain. Such an intervening stage in the drainage seems to harmonize well with the browner color of the lower layer and with the division recognized between the lower and the upper layers, the latter of course being the assigned work of the resumed aggregation on the surface of the old plain.

To fill out a fair recognition of the inevitable mixing processes to which the creek deposits were subject in the course of their accumulation, several incidental activities should be noted, the most important of which perhaps is the overturn of the trees that grew on the bottoms; but this paper would grow tedious if these and other incidental modes of mixing were discussed in detail.

b) Suggestions stimulated by the outer relations of the creek-deposits.—Whatever the above suggestions might contribute toward the interpretation of the crowded and mixed association of the fossils and relics in the six feet of creek deposits, if put into service, they would still leave no little apparent conflict of evidence connected with the neighboring and also with the more remote relations of the deposit.

Geologists studying these outer relations, either from the physico-dynamic point of view or from the regional point of view, are confronted with difficulties that naturally cause them to hesitate to believe that the time since the Vero Ridge was formed—which is somewhat greater than the time since the creek deposits began to be formed—can be the record of all that was done here since the Early or Middle Pleistocene. Inevitably then the presence in the beds of extinct mammals that have been regarded as evidence of these early stages raises a serious question as to which class of criteria is the more trustworthy.

Anthropologists naturally hesitate to believe that the Indian type of skeleton could have remained without appreciable modification for forty-five hundred centuries—the minimum date assigned the Aftonian stage in our tentative time-scale—or for any notable part of that long period, and so on these grounds also the question of the relative value of criteria is raised. In this case, interestingly enough, the conflict of evidence takes the form of bone against bone.

The archaeologists are naturally still more hesitant to believe that Indian pottery-making could remain in a static state for the period named or any period measured by hundreds of centuries, not to say thousands of centuries, for when a plastic art is set over against the evolution of biotic species, the presumption of the speedier change lies much in favor of the art.

The paleobotanical evidence has been interpreted as implying a much shorter period than do the mammalian remains between the lower and the upper deposits of the creek series. The general presumption of changeableness, however, has commonly been held to favor the mammals.

Marine paleontology seems to be rather neutral in this war of criteria. The marine layer that underlies the beach ridge in which the creek sank its valley and later began to fill it contains few fossils, if any, of species other than those now living. Using the inherited organic criteria, the age of this layer has usually been placed at or near the end of the Pleistocene Period. It would seem to be a fair accommodation to the general tenor of the various evidences to make the last retreat of the sea from the mainland in the Vero region the beginning of the Recent Period. Such a reference, however, places the *beginning* of the creek deposits *within* the Recent Period. This conforms very well to the apparent requirements of regional geology, of physical geology, of anthropology, and of archaeology. Perhaps paleobotany might be accommodated to it without putting its data under much strain if any at all; but vertebrate paleontology, especially mammalian paleontology, as heretofore understood, would apparently need radical revision. The suggestion here implied, that the extinct mammals may have lived on even into the Recent Period, goes a step farther than the suggestion made at the conferences to the effect that the several vertebrates heretofore only known to occur in Early or Middle Pleistocene beds really lived on in this southern clime until a much later Pleistocene date. Even then it is not necessary to suppose that the older of these extinct mammals were contemporaneous with man, for the two hundred centuries assigned to the Recent Period give room for appreciable differentiation. Obviously this basis of reconciliation throws the burden of revision most heavily on vertebrate paleontology and subordinately on paleobotany.

Those who are thus hypothetically made to bear nearly the whole burden of revision are entitled to trial hypotheses which shall in a like hypothetical way throw the burden of revision on other criteria. The method of multiple working hypotheses, in

its eminent fairness, requires us to make an earnest effort to bring under trial all tenable alternatives, to the end that among these there may be found the one that apportions the task of revision in strict accord with the inherent value of the combined evidence. This in its very nature also covers the question whether or not it is possible to escape all serious revision of criteria by finding some tenable basis of reconciliation not perhaps now recognized.

How such a series of multiple working hypotheses is to be built up from the one we have just suggested is almost obvious, for the one just offered is a rather extreme one and quite suitable to form the end hypothesis nearest us in time. To build out the series from this backward in time, it is merely necessary to push back step by step the assigned place in time of the basal creek deposit and note the degree of strain put on each of the several criteria of interpretation by each step. The measure of total strain in each case—or the best balance of such strain as is unavoidable—forms the index of success of each trial hypothesis.

In studying such a series it will be not only interesting but significant to note that, if we accept the interpretation of the creek deposits already sketched, the extinct vertebrates may be assigned earlier and earlier ages without necessarily bringing any strain at all to bear upon the archaeological and anthropological evidences, for the human relics were buried at horizons so close under the deposits in process of formation when suspended in 1913 that any tenable amount of backward assignment of the content of the lower layers is not likely to carry these relics back beyond the place their own criteria would assign them on independent grounds. The strains that are really brought out by such backward steps in assignments of the date of deposition of the extinct vertebrates or of the plants bear almost solely on the criteria derived from physico-dynamic and regional considerations. The question of the Pleistocene or the non-Pleistocene age of man is thus replaced by the much broader and deeper question, What are the relative worths of the criteria offered by life-extinctions on the one hand, and those offered by physical state, dynamic work done, regional distribution and stratigraphic arrangement, on the other?

In any attempt to rectify the criteria, there is a prerequisite that is strictly indispensable, to wit, the keen recognition that relics buried beneath secondary or tertiary derivatives from the surficial deposits are little better than Mephistophelian in their insidious power to deceive. A relic reported as found beneath twelve feet of gravel or twenty feet of loess by anyone not trained to avoid these Mephistophelian lures is to be held as quite without value until tested; it merely serves as an interrogation point to punctuate the question, Is it worth while to investigate the case?

c) The deeper and broader issues involved in the Vero case.—The more profound interest of studious men of science lies in such advances in modes of inquiry, such increases in the trustworthiness of criteria, such larger hospitality to working alternatives, such greater readiness to make trial of these and frankly lay them aside if found wanting; such hospitality to revision, and such larger views of the whole problem as may be drawn out from the case. Let us therefore survey from a more general point of view the main lines along which this problem may be approached with the hope of important light. Foremost among these are: (1) the extinction of biotic species; (2) the introduction of biotic species; (3) the physico-dynamic vestiges; and (4) the regional relations of the formations; the rest must be omitted. The leading criterion of the first is *life gone out;* of the second, *life come in;* of the third, *work done;* and of the fourth, *the deployment of the record.*

(1) In approaching a problem on the first line, it has been customary to bring to bear the times of extinction of the species of faunas and floras that lived in the stages immediately preceding and the ratios of such extinct forms to the living species present. Some advances on the older methods are to be noted. Chief among these is the appeal to causes of extinction as confirmatory evidences. This relates the statistical method to the dynamic method; it helps to co-ordinate the facts of extinction with the work of the agencies that produce extinction. This has chiefly been a co-ordination of faunal changes and glacial climates. Further deployment in this and other directions is much to be desired. As a suggestion in that line, why should not the

northward advance of pathogenic microbes, assignable to the rise of temperature as an interglacial epoch comes on, be quite as plausible a cause of extinction as the southward advance of a cold climate as a glacial epoch comes on? In this particular case may not the advance of the warmth of the early Recent Period have thus been indirectly one of the effective causes of that rather remarkable rate of extinction which seems to be recorded in the six feet of the creek deposits at Vero?

(2) The second line of approach has not been sharply distinguished from the first, nor has it been brought into equal use as a means of discrimination, as the discussion of the Vero case very pointedly shows. Has not the introduction of species, however, resources of discrimination equal to those of extinction, if not indeed greater? In the use of extinctions the inquirer can only start with the imperfect knowledge of earlier faunas and floras. He can only trace these forward to disappearance by means of the inferior record of those earlier times. On the other hand, in the use of the introductions of species, it is possible, by reversing the time-order, to start with the fuller knowledge of the present faunas and floras and trace these backward by the use of the more complete record of recent times. There may thus be brought into use a large amount of data relative to the climatic adaptations of existing species, varieties, and races, and hence by inference, knowledge of the climatic conditions that obtained when these were introduced. By starting with the richer resources of the biologic knowledge of the present and the fuller knowledge of present conditions, there is good reason to hope that before the preceding records grow too obscure, the climatic effects of the last ice invasion even upon southern faunas and floras may be detected, and so the southern fossil records rendered directly comparable to the glacial record.

Now it is highly pertinent to the question at issue to observe that the extinctions and introductions of biotic species, varieties, and races during the last century have been phenomenal in kind and degree. Within the memory of some of us that are older there have been profound changes in the general aspect of the regional faunas and the floras in North America more radical,

perhaps, than were witnessed by the preceding ten generations. That there was a special biologic cause for this only intensifies its importance as a subject of special study. It is such critical events in history that should put us on our guard, for similar critical events probably characterized all the past, as LeConte so wisely urged on our attention.

Co-ordinate with this a like radical change has taken place in the rates of erosion, sedimentation, and the surficial aspects of the land. These climacteric stages in the extinction of species, in the introduction of species, and in surficial evolution furnish stimulating grounds for revision of ideas and a reconstruction of working tenets. They offer a point of departure of most suggestive value.

A very vital phase of this recent physico-dynamico-bio-psychic combination is human art and industry. This becomes a very important additional resource in discrimination. The evolution of the arts and industries is usually far more rapid and much more sensitive to conditions than the evolution of biotic species. It is in like degree a more refined criterion of historical progress.

(3) The third line of approach is an endeavor to find in the record of work done by the chief terrestrial agencies a basis for the natural events that mark off the progress of the ages. These agencies are more or less rhythmical in action and so reach climaxes here and there that serve for dividing lines or points of reference. To a large degree these agencies are the basal causes of the leading events of the geologic record. As such basal causes they are eminently fit for true criteria. Concretely, the physico-dynamic agencies record themselves in changed relations of land and sea, in changes of surface attitude, in changes of soil growth, of denudation, of configuration, and of sedimentation, as also in changes of climate, and of most other environing features that condition life. We have already remarked that glacial invasions and glacial oscillations have already in large measure replaced the older criteria on which are based the divisions of the Pleistocene Period and its separation from the Recent Period. A greatly enlarged use of these newer physico-dynamic criteria is scarcely less than imperative to conclusions that will stand the tests of the future.

(4) The help derivable from the spacial or positional relations of the deposits is most conveniently summed up in the term regional relations, and is best illustrated concretely. Between the Vero location on the very edge of the continent—far to the south—and the glacial formations in middle latitudes, there is a wide stretch of territory covered by Pleistocene and Recent formations, each of which has its place and significance in the recent history of the whole region. Whether we are able to distinguish all these or not, they are there and have their story to tell. These must ultimately be assigned their true place in the natural series that intimately connects the Vero deposits with the glacial formations in the northern states. These fall into four geographic provinces suited for work on the problem in hand. In the working of these provinces, of course, the extinctional, the introductory, and the physico-dynamical methods of inquiry should each play its own appropriate part. The following regional work is definitely indicated:

(*a*) Intensive and correlative work on the marine coastal tracts of the Atlantic and the Gulf. By this connection would be made between the glacial and glacio-natant deposits of the North and the contemporaneous marine deposits of the warm South. In this work the distinctive marine criteria, physical and biotic alike, should be adhered to rigorously and all formations not amply accredited by marine credentials should be left in the waiting list, or placed elsewhere.

(*b*) Inland from this narrow coastal tract, a broad U-shaped tract wraps about the Appalachians with its outer southeastern flank against the sea deposits of the Atlantic and Gulf on the one side and its inner northwestern flank on the glacial deposits of the Ohio Valley on the other, while at the top of the U these tracts abut against the glaciated areas on either side of the mountains. The strategic advantages of working this province as a unit are obvious. The aggradation-degradation deposits on the two flanks of the Appalachians offer special advantages in correlation and in interpretation.

(*c*) The fluvial deposits of the Mississippi Valley, embracing those whose sources lay in the glacial-drainage area of the upper

Mississippi Valley, offer a highly promising line of inquiry in which definite glacial-drainage stages may probably be traced into physical connection with both the terrestrial and the marine deposits of the more southerly regions.

(*d*) The lowland and upland plains west of the Mississippi offer a similarly promising connecting tract between the Keewatin glacial fields and the Gulf coast.

The combined import of careful co-ordinated studies on these promising connective tracts between the fields of warmth and the fields of cold should greatly help in revising and reconciling the discordant interpretations so notably brought out—so fortunately brought out, shall we say,—by the singularly suggestive deposits at Vero.

INEQUALITIES OF SEDIMENTATION[1]

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CONTENTS

INTRODUCTION

Most of the earlier discussions touching the subject of sedimentation leave in the mind of the reader the impression that water-laid sediments other than delta deposits accumulate over very wide areas at a nearly uniform rate. Leaving out of consideration delta and estuarine sediments whose relatively rapid accumulation is of course universally recognized, variability or contrast in rates of deposit between different areas and between different periods in the same area rather than uniformity appears to the writer to be the dominant feature characterizing sedimentation. In both its time and space relations sedimentation is highly variable.

[1] Published with the permission of the director of the Geological Survey of Canada.

It is the purpose of the present paper to point out some of the factors which make for periodic variability in the rate of deposition and to cite some examples from existing lakes and seas to illustrate the sharp contrasts in the rate at which sediments accumulate at different points near the same coast line.

Some familiarity with the mobility of wind-formed deposits is unavoidable, but with the far greater mobility of water-laid deposits we have a comparatively slight acquaintance. We are apt to think of clastic deposits which have once come to rest on sea or lake bottom as permanently fixed. That such materials lose nearly half their weight in water and in a corresponding degree their tendency to "stay put" is apt to be forgotten in considering the history of geological formations. Removal or migration of parts or the whole of an unconsolidated formation may occur much more rapidly below than above sea level. The buoyancy of water, together with the general absence of the fixing influence of vegetation, gives to unconsolidated aqueous deposits under the combined influence of waves and currents a far greater degree of mobility and instability than subaërial deposits possess.

CLASTIC DEPOSITS

Observations on the Great Lakes.—Previous to human interference sand dunes represent in a moist climate an established equilibrium between the forces of the winds and the waves and the stabilizing influence of vegetation. The slightest interference by man with the vegetable covering of a sand hill country which is usually found in temperate climates may, however, start the dunes of a whole region traveling. It is said that the highest dune of Friesland owes its origin to the destruction of a single oak. Water-laid deposits represent a similar balance of forces in which water currents replace air currents.

The deposits of the foreshore represent the innermost zone of sedimentation. They may be examined in part at least from the vantage ground of the shore. Because of their comparative accessibility to observation the deposits of bars, tickles, and spits illustrate well the irregular and highly localized character of the inshore deposits.

The shores of the Great Lakes afford examples of these massed aggregations of sand and gravel flanked by extended areas of shoreline along which little or no deposition of sediment occurs. The south shore of Lake Erie east of Sandusky is nearly everywhere composed of Devonian shales or glacial till, the wave and current action being destructive instead of constructive. At Erie, Pennsylvania, however accretion dominates the elsewhere prevailing erosion and a long, broad spit has been built into the lake inclosing Erie harbor.

On the Canadian shore of Lake Ontario at Toronto, in sharp contrast with the bare rock bottom frequently found near the shore of Prince Edward county, there is a sand spit building out into water nearly 200 feet deep. In the Burlington bar which extends from the north to the south shore of Lake Ontario five miles from the western end of the lake we have in the maximum depth of the enclosed lagoon, 80 feet, an approximate measure of the total thickness of the bar deposit which has been built up during the relatively short life of this lake. Convincing evidence that bars form even far more rapidly than such a figure would suggest is furnished by the observations of Russell[1] on a bar at Round Island in Lake Huron. Two photographs by Russell taken ten years apart show that the bar increased 1000 feet in length during this interval. Observation of the movement of littoral drift along the shore of Lake Ontario affords equally clear evidence of the rapid movement of very coarse sediments and shingle. In the vicinity of Oakville the littoral drift is westward. Two piers built out into the lake at this point on opposite sides of a river mouth to protect navigation act as groins. Nothing accumulates on the beach behind the west pier, thus showing that there is no movement of material toward the east. Alongside the east pier, however, the beach is growing out into the lake and during periods of rough weather the westerly moving shingle nearly overwhelms the base of the pier and the building near it.

In the Great Lakes the vigorous action of currents is by no means confined to the immediate vicinity of the shoreline. A

[1] Russell, "A Geological Reconnaissance along the North Shore of Lakes Huron and Michigan," *Geol. Surv. of Michigan* (1905), p. 104, Pl. 15.

curious feature of their behavior is its capricious character, reminding one of fitful gusts of wind on a stormy day. A single excerpt from the notes of Mr. E. J. Whittaker on the behavior of currents in Lake Erie 2 miles south of Point Pelee will illustrate this.

> Water depth 18–20 feet; float at depth of 15 feet; average current rate 1.91 miles per hour. Current here alternately slackened and quickened. Off this point I also got a good illustration of this with a small motorboat while soundings were being taken by Philp's men. The motorboat running at perhaps 2½–3 miles per hour for intervals of three minutes at a time was unable to make any headway at all. The current then suddenly slackening, the boat would fairly bound forward as though released from a chain. This was the most notable instance of a strong varying current. Moreover here the current changed its direction completely inside of 45 minutes, first being a strong easterly current and at the conclusion of observation being from the west.

In direction the lake currents are variable but only within certain well defined limits. At Southwest Shoal light-ship, a short distance from the station referred to above, current observations which continued over a period of two months during the summer of 1918 showed easterly and westerly currents with about equal frequency but no other direction is represented. Another Lake Erie station which was occupied for some weeks shows only southerly currents. It is therefore certain that the work accomplished by lake currents is not of a haphazard character and that some of their general results in sedimentation can be inferred with certainty when a sufficient amount of data on their behavior becomes available.

Littoral marine deposits.—The movement of sediments along the shores and over the bottoms of the Great Lakes, although it is considerable, is far outclassed in volume by the material which is constantly passing over the littoral zone of many sea coasts. The construction of harbor defenses against the sea sometimes affords surprising evidence concerning the volume of sediments which moves along the sea bottom in front of the foreshore. Instructive evidence concerning the great volume of such traveling sediments on some parts of the sea shore is furnished by the history of the Madras Harbor in India.

> The Indian Government in 1876 determined to construct an enclosed harbour at Madras. Careful observations were made of the volume of sand travel, and it was estimated that it would take 180 years for the travelling

sand to fill a triangular area between the coast line and a breakwater running out 1,200 yards from the shore. No sooner, however, were the works commenced than it became obvious that the above estimate of sand travel was completely unreliable. The wave-borne sand travelling up from the south was about sixty times greater in volume than the corresponding amount brought down by the northeast monsoons. The original estimate of sand in motion was 243,000 tons per annum; a second estimate in 1904 was 550,000 tons per annum. The accumulation at the present time shows that about 1,000,000 tons per annum travel along the coast line. Low-water line between 1876 and 1912 has crept seawards for a distance of 2,500 feet. In 1881 a terrific cyclone wrecked the harbour works then nearly completed but a somewhat similarly outlined harbour has since been carried out on altered lines. For a distance of more than 3 miles severe erosion has taken place on the north side of the harbour due to the arrest of the normal volume of travelling sand, and whole towns and villages have thus been swept away. This experience is an extreme instance of the action which goes on in a greater or less degree at every headland, river-mouth or solid projection from a foreshore into the sea.[1]

It may be noted here that the migration of clastic materials in the littoral zone is not confined to the finer products of erosion but comprises much coarse material and even heavy blocks of stone.

Rollers bring in shingle and sometimes large masses of rock from deep water. It frequently happens that, after a severe gale in the channel, boulders weighing several hundredweight will be found strewn along the strand. These are mostly weed-covered. The growth of weed evidences the fact that the action of the waves has reached sea depths normally tranquil. In exposed portions of the coast line of Scotland boulders upwards of 2 tons in weight are similarly thrown up after storms and their occurrence on these spots is so much a matter of course that they go by the name of "travellers." Their buoyancy being increased by the crop of seaweed they carry, they are pushed along the sea bed under the impulsion of the deep-water rollers. As an instance of deep-sea wave action may be cited the fact that concrete blocks at Peterhead harbour weighing 47 tons were forced out of position at a depth of 40 feet below low water.[2]

The English Channel is an area over much of which clastic sediments pass without stopping to build up formations. The detailed explorations of the bottom of the English channel made by

[1] A. E. Carey, "The Sanding up of Tidal Harbours," *Proc. Inst. C.E.*, CLVI (1903–4), 1–90; A. E. Carey and F. W. Oliver, *Tidal Lands*. Blackie & Sons, Ltd., (1918), pp. 144–45.

[2] *Op. cit.*, p. 150.

French engineers[1] many years ago in connection with the proposed submarine railway tunnel showed the sea floor to be free of unconsolidated or recent deposits from the French to the English coast between Dover and Calais. Because of the prevailing westerly and southwesterly winds the normal littoral drift in the English channel is eastward, so that most of the detrital material which passes through it doubtless comes to rest in the North Sea. Much of the coarse materials stop on the Dogger bank. This bank which is bounded by the 20-fathom line and covered by quartz sand is comparatively free from the finer silt which occurs in the deeper parts around it.[2] The sand and mud formations now forming in the North Sea represent the time interval since the submergence of the North Sea and English Channel area. These deposits probably thin out gradually toward the Channel where this considerable time interval is entirely unrepresented by any sediments. This it will be noted gives a relationship of areas where a formation is absent, relatively thin, and comparatively thick, which when met with in the consolidated rocks is generally ascribed to overlap. The Potsdam sandstone of New York and Ontario affords a comparable example. It is absent in the upper Ottawa valley, less than 100 feet thick over much of the southeastern Ontario but reaches a thickness of several hundred feet in eastern New York. Its progressively decreasing thickness from Lake Champlain to Ottawa is generally ascribed to overlap.

In the enclosed Arctic seas west of Greenland McMillan reported currents with a usual velocity of about 2 miles an hour.[3] In the same region Low has made the important observation that

> With bodies of water having a general north-south trend the current will flow north on the east side and south on the west side while in east and west bodies the direction will be west on the north side and east on the south side.[4] On the Greenland side a southerly current comparatively free of ice allows the

[1] A. Strahan, "The English Channel," *Nature*, XXV (1882), 463–67; *Lond. Geóg. Jour.*, XXXI, 420.

[2] *Royal Comm. on Coast Erosion and Afforestation*, III (1911), Part 1, p. 9.

[3] J. G. McMillan, *Report of the Cruise of the Dominion Government Steamer Arctic in Northern Waters, etc., in 1908-9*, p. 469.

[4] A. P. Low, *Cruise of the Neptune* (1906), p. 289. Canadian Government.

open sea to raise the general temperature while on the Elsemere side the Arctic current with its continuous stream of ice blocks the bays and does not allow the open water to ameliorate the cold of the ice covered lands.

It is evident that currents trending in opposite directions on opposite sides of narrow sea ways will tend to develop marked contrasts in the kind as well as in the amount of sediments which they distribute in comparatively limited areas.

In Chesapeake bay Hunter has shown that both erosion and accretion are contemporaneously in progress in adjacent parts of the bay. He finds that in the area studied, "The areas subjected to erosion aggregate 35 square miles and those subjected to sedimentation 9 square miles, making an excess of 26 square miles eroded."[1]

In the Bay of Fundy the processes of deposition and scour are both active as Matthew[2] has pointed out. His statement is summarized as follows:

In the Bay of Fundy the velocity of the tide varies from two to three knots at its mouth to seven or eight knots in the Parrsboro passage near its head. Near its mouth, on the New Brunswick side, a portion of the bay is separated by a chain of islands, and is called Passamaquoddy Bay. . . . . The rush of the tide through these passes causes a roaring sound which may be heard for many miles, and the whirlpools in them are strong enough to upset boats and careen large vessels; both channels are full of deep holes, ledges, and pointed rocks. At Quoddy River the tide passes over barriers having only fifteen fathoms of water at low tide, yet within owing to the erosion of the tidal currents, there is fifty fathoms in the narrowest and straightest part, and thirty fathoms where it merges into the shallower water of Passamaquoddy Bay. . . . . Up in Chignecto Passage also off Cape Enrage, there is a trough scooped. out by the tide, which is outlined by the thirty, twenty-five, and twenty-fathom contour lines. . . . . But it is in the eastern arm of the Bay of Fundy—Minas Channel and Basin—that the scouring action of the tide is most conspicuous. . . . . The violence of the current in the deep troughs of Minas Channel and Basin occasions the roughest bottom observable anywhere in the bay, for at these points rock and gravel compose the bottom over which the tidal waters run. . . . . The north side of the Bay of Fundy having the slower run of tide, and being that along which the principal rivers enter, has in parts a muddy

[1] J. F. Hunter, "Erosion and Sedimentation in Chesapeake Bay around the Mouth of Choptank River," *U. S. Geol. Surv. Prof. Paper 90B* (1914), p. 14.

[2] G. F. Mathew, "Report on the Superficial Geology of Southern New Brunswick," *Can. Geol. Surv. Rept. of Prog. for 1877–78* (1879), pp. 18EE–22EE.

bottom. The only mud-bank of considerable volume is that formed by the sediment which the St. John River carried to the sea. It begins at the harbor of St. John and extends westward along the coast as far as the small islands called The Wolves, its outer limit coinciding nearly with the fifty fathom line. . . . . As a rule where the movement of the current exceeds one and a half knots mud is not deposited on the bottom of the bay.

Current work in deep water.—It must be pointed out that non-deposition and scour is not confined to shallow and narrow sea ways. Ocean currents are known to sweep the sea floor at considerable depths and at considerable distances from land. At the head of the Bay of Bengal the great delta deposits of the Ganges and Brahmaputra rivers are interrupted by a deep channel called the "Swatch of no ground" which is kept open presumably by some acceleration of the tidal currents. This channel which has a depth of 200 to 300 fathoms terminates abruptly on the west side in water only 5 to 10 fathoms deep.[1] Thus we have in the midst of an area in front of the mouths of the two greatest rivers of India where sedimentation proceeds with great rapidity a belt of sea bottom where deposition is supplanted by scour.

Off the west coast of Scotland tidal currents of great strength are known at some points to sweep the bottom at a depth of nearly 100 fathoms. Between Glas Island and Sgeir-i-Noe in the Little Minch off the west coast of Scotland the flood-stream often takes the buoys of the long lines down "and it is a remarkable circumstance, indicative of the great depth of the tidal-stream here, that the buoys though anchored in 70 or 80 fathoms are taken completely to the bottom; starfish and other marine animals being found attached to them."[2]

The laying of the transatlantic cables brought to light evidence of powerful currents at unexpected depths.

Perhaps the most marked experience we have had of currents at great depths was in the case of the Falmouth cable near Giberaltar. At 500 fathoms the wire was ground like the edge of a razor and we had to abandon it and lay a cable well inshore. Captain Nares, of the surveying ship *Nemesis*, I

[1] James Ferguson, *Quart. Jour. Geol. Soc.*, XIX (London, 1863).

[2] *Sailing Directions for the West Coast and Islands of Scotland from the Mull of Cantyre to Cape Wrath*, p. 119.

think, with tangles could get no specimen of the bottom whatever, and he thinks he got sufficient evidence to prove the existence of a perfect swirl at that depth. . . . .[1]

South of the Azores, Hjort found considerable tidal currents down as deep as 800 metres.[2] Reade[3] has pointed out the evidence which certain relatively deep soundings afford regarding the irregularity of deposition. "In the Little Minch there is a 'deep' between the Isle of Skye and North Uist with a sounding of 107 fathoms, 'rock' the surrounding bottom with soundings from 50 to 90 fathoms being shells, sand, or mud."

Between the island of Rum and the island of Barra there are a good many soundings showing rock, which are deeper than others in the vicinity which have muddy bottoms.

If we find hard ground we know that there must be something to prevent the accumulation of sediment. Now the only thing that prevents the accumulation of sediment is a current, and one help that telegraph soundings have thus given to geographical science as an indication that tidal currents exist even at very great depths in the open ocean.[4]

Most if not all deep-sea naturalists have noted even in the deeper parts of the continental shelf evidences of current action. Verrill has pointed out in the following quotation how such currents over certain areas southeast of New England have prevented the formation of argillaceous sediments.

The prevalence of fine sand, along the Gulf-stream slope in this region, and the remarkable absence of actual mud or clay deposits indicate that there is here at the bottom, sufficient current to prevent for the most part the deposition of fine argillaceous sediments over the upper portion of the slope, in 65 to 150 fathoms. Such materials are probably carried along till they eventually sink into the greater depths nearer the base of the slope or beyond, in the ocean basin itself where the currents are less active. It is probable

[1] Quoted by T. Mellard Reade, in "The North Atlantic as a Geological Basin," Presidential Address, Liverpool Geol. Soc. Session, 1885–86.

[2] Johan Hjort, "The Michael Sars North Atlantic Deep-Sea Expedition 1910," *Geog. Jour.*, XXXVII, 349–77.

[3] T. Mellard Reade, "Tidal Action as an Agent of Geological Change," *Philosophical Mag.*, XXV (1888), Series 5, p. 514.

[4] *Ibid.*, p. 514.

that such a movement of the water may be partly due to tidal currents, as well as to the actual northward flow of the Gulf Stream which is here slow, even at the surface.[1]

Charles Darwin long ago discussed some of the striking examples of inequalities in sedimentation which occur in the Red Sea and in the West Indies. The extent to which the significance of his very important observations appears to have been neglected by geologists may justify the following quotations from them.

The area of deposition seems less intimately connected with the debouchment of the great rivers than with the course of the sea-currents; as is evident from the vast extension of the banks from the promontories of Yucutan and Mosquito. . . . .

Besides the coast-banks there are many of various dimensions which stand quite isolated; these closely resemble each other; they lie from 2 or 3 to 20 or 30 fathoms under water and are composed of sand, sometimes firmly agglutinated with little or no coral; their surfaces are smooth and nearly level, shelving only to the amount of a few fathoms very gradually all round towards their edges, where they plunge abruptly into the unfathomable sea. This steep inclination of their sides which is likewise characteristic of the coast banks is very remarkable: I may give as an instance, the Misteriosa Bank on the edges of which the soundings change in 250 fathoms horizontal distance from 11 to 210 fathoms; off the northern point of the bank of Old Providence in 200 fathoms horizontal distance the change is from 10 to 152 fathoms; off the Great Bahama Bank in 160 fathoms horizontal distance the inclination is in many places from 10 fathoms to no bottom with 190 fathoms. On coasts in all parts of the world where sediment is accumulating something of this kind may be observed; the banks shelve very gently far out to sea and then terminate abruptly. . . . . I may observe, although the remark is here irrelevant that geologists should be cautious in concluding that all the outliers of any formation have once been connected together for we here see that deposits, doubtless of exactly the same nature, may be deposited with large valley-like spaces between them. . . . . [2]

I may instance the great banks of sediment within the West Indian Archipelago, which terminate in submarine slopes, inclined at angles of between 30 and 40 degrees, and sometimes even at more than 40 degrees. . . . . That in some cases, the sea instead of spreading out sediment in a uniform sheet, heaps it round submarine rocks and islands it is hardly possible to doubt, after having examined the charts of the West Indies.[3]

[1] Verrill, "Marine Faunas off New England Coast," *A.J.S.*, XXIV (1882), 449.

[2] Charles Darwin, *Geological Observations* (1851), Part I, pp. 196–97.

[3] *Ibid.*, Part II, pp. 133–37.

In the light of the abundant evidence it is hardly possible to doubt that currents play a great rôle in localizing the accumulation of sediments. In the words of the late Clement Reid:

> There is a general impression that marine action cannot go on much below low water; but this is altogether a mistake. Tidal scour may go on at any depth, provided the current is confined to a narrow channel, so as to obtain the requisite velocity. If in addition there is a to-and-fro motion such as that caused by the Atlantic swell at depths of at least 50 fathoms, the actual current required to remove even coarse sand need only be very gentle. The oscillation in one direction may not reach the critical velocity; in the other this velocity may just be exceeded; the movement, therefore, of the sand grains may always be in one direction especially if the courses taken by the ebb and flood tides do not coincide, or their velocities differ.[1]

The relative importance in sedimentation of the rôle of wave action which is constantly before our eyes is apt to be overestimated. Current action which even when most vigorous is seldom visibly in evidence is apt on the other hand to be unduly minimized.

Shifting of deposits.—The power of currents to transport sediments is nearly everywhere subject to periodic variations resulting from the influence of storms. In some regions there appears also to be a seasonal acceleration and retardation of tidal currents. Branner was told by a pilot on the Brazilian coast "That the currents inside of the Abrolhos and Parcel das Peredes reefs set strongest to the southwest in May, June, and July; that they run in the same direction at other times of the year, but not so strongly." Such variations in current velocity must result frequently in considerable deposits being laid down and subsequently removed by the same current.

A change in depth of wave base and in the courses of currents resulting from the elevation or depression of a coast line may result in shifting the position of an entire formation. As Vaughan Cornish[2] states, "A very small disturbance of conditions if long continued can shift the largest shoal. Such a disturbance is the recession of the coast line. It is probable that a shoal off the coasts

[1] Reid, *Submerged Forests* (New York: G. P. Putnam's Sons, 1913), p. 85.

[2] Cornish, "On Sea Beaches and Sand Banks," *Geog. Jour.*, XI (1898), 641.

of our eastern counties [England] tends to travel at the same rate as the coast is cut back."

Observation of surface currents alone will afford no positive evidence concerning the direction in which bottom formations are growing, nor their source. On the shoal east of Gorda bank the direction of the flow is nearly at right angles to the surface current. North of Barbados 60 miles Pilsbury[1] found at different levels between the surface and 200 fathoms, currents flowing in three different directions, simultaneously the lower at right angles to the surface.

Relative aridity.—The average annual loss by erosion is 95 tons for every square mile of the United States, excluding the Great Basin, according to an estimate published by the U.S. Geological Survey. The enormous volume of sediment which this contribution from nearly 3,000,000 square miles yields is distributed around the continental shelf of North America with a degree of irregularity corresponding to a number of variable factors. Among these factors are the variability in the rate of rainfall, location of river mouths, the direction and velocity of air currents, and the strength and direction of tidal currents. The interplay of all these and of various other factors will doubtless result in building on parts of the continental shelf deposits of great thickness and very considerable extent. Over other extensive areas nothing at all will be left by the ocean currents, and scour may result. The general result may be an irregularity of deposition as great as that which characterizes wind-blown deposits.

The comparatively small volume of clastics which an arid region like western Australia could furnish to its extended littoral zone would result in a minimum rate of deposition which would probably be much lower than that of any other continental coast line. This vast region which is essentially a desert coast line of about 3,500 miles has not a single river of any size. The so-called rivers are mostly insignificant streams many of which are nearly dry unless during the rainy season.[2]

[1] Pilsbury, "The Gulf Stream; Methods of the Investigations and Results of the Research," *Rept. U.S. Coast and Geol. Survey* (1890), Appendix 10, p. 570.

[2] Henry M. Cadell, "Some Geological Features of the Coast of Western Australia," *Edinburgh Geol. Soc. Trans.*, VIII (1899), 174.

If with the littoral zone of western Australia such an area as the Bay of Bengal is contrasted, the enormous difference in the volume of clastic sediments which comes to rest on different parts of the sea bottom is clearly seen. The upper part of the Bay of Bengal receives the drainage from the southern slopes of the Himalaya Mountains where in places the rainfall amounts to 472 inches or nearly 40 feet per annum.[1]

Rôle of vegetation in estuaries.—Closely related to the relative aridity of the sea coast in different parts of the world is the variable rate at which sedimentation on different coasts transforms shallow estuaries into marshes and eventually into dry land. When sedimentation has developed to the stage of shifting sand banks in an estuary, vegetation becomes the chief factor in fixing these and in extending land conditions. In an arid climate the virtual absence of this factor may cause the last stages of filling to proceed with extreme slowness while in a moist climate they will develop with relative rapidity. The rôle of vegetation as a factor in late stages of sedimentation is well illustrated in Professor Oliver's study of the plant life of a salt marsh in Brittany called the Bouche d'Erquy.

> Sand litters the beach, and in part is blown by the winds to form the barrier of sand dunes. Another part is brought into the estuary and is driven hither and thither by every tide. So restless are the shifting sands in the lower part of the estuary that plants cannot gain a footing, though seed be scattered far and wide. Higher up as we saw stability has been reached, and the ground is held by a turf of halophytes, and half way up the estuary where the bare and covered parts adjoin, the restless sands are tamed and bound. The transition from the fixed marsh to the mobile sand is a gradual one. The continuous carpet of the former gives place to scattered hummocks or tussocks of *Obione portulacoides* and the perennial *Salicornia radicans*. Beyond this the *Obione* dies out and the *Salicornia radicans* carries on its colonizing work alone. This it does by throwing out each year its seeds which germinate on the treacherous sand. . . . . In some places the pioneers are advancing at a rate of 10 feet a year, elsewhere less rapidly; whilst in spots where the sand is very mobile they seem perfectly stationary but the local conditions are always changing and the most unpromising surroundings may give place at any time to such as favour a rapid advance. A rough estimate based on the rate of progress noted during the last three years and on the assumption that this rate will

[1] G. T. Bonney, *The Structure of the Earth*, p. 40.

not be checked would indicate that two hundred to two hundred and fifty years must elapse before the whole estuary is carpeted with halophytes.[1]

Periodic and cataclysmic variations.—Variations in sedimentation which correlate with a time factor may be referred to two classes: (1) periodic or seasonal, and (2) those without any definite period of recurrence which may be termed cataclysmic. To the first class belong the differences in the quantity of sediment which is deposited on a delta front during the spring flood period and the winter season. Such differences may be recorded in banding or lamination similar to those which Sayles[2] has interpreted as of seasonal origin in certain aqueoglacial deposits. To the cataclysmic order of variability belong the profound alterations in coast lines and in shifting of the sediments near them which result from phenomenal tides, great storms, and tidal waves. The Bay of Fundy has furnished a good example of tides of extraordinary height in the Saxby tide, which accompanied the heavy Saxby gale of October 5, 1869.[3] The destruction of the city of Galveston a few years ago, resulting from the piling up of sea water on a low shore by a great storm, illustrates well the profoundly destructive character of storms of maximum intensity which may recur only at intervals of one or more centuries. The folklore of many races affords evidences of such phenomenal disturbances in the normal relations of land and sea in the form of legends regarding a universal deluge.

The rise of the sea to an unusual height resulting from tempests of exceptional violence over low-lying lands which occurs at widely separated intervals along some coasts has frequently resulted in sudden and most comprehensive alterations of the physical geography. The piling up of the water of the North Sea on the north coast of Holland has repeatedly resulted in submergence and great disaster to extensive areas in Holland within the historical period. It is estimated that 2,336 square miles[4] have been swallowed by the

[1] F. W. Oliver, "An Experiment in Co-operative Fieldwork in Botany," *The Southeastern Naturalist* (England, 1907), p. 41.

[2] R. W. Sayles, "Seasonal Deposition in Aqueoglacial Sediments," *Mem. Mus. Comp. Zoöl.*, XLVII (1919), 1–63, pls. 1–16.

[3] Robert Chalmers, *Can. Geol. Surv. Ann. Rept.*, Vol. 7, n.s., 1894 (1896).

[4] E. Reclus, *The Earth and Its Inhabitants*, III, 462.

sea in Holland since the thirteenth century. One of the most remarkable of these changes produced the Zuyder Zee. In the thirteenth century

> the low lands along the Vlie, often threatened, at last sank in the waves. The German Ocean rolled in upon the inland lake of Flevo. The stormy Zuyder Zee began its existence by engulfing thousands of Frisian villages, with all their population and by spreading a chasm between kindred peoples.[1]

The political as well as the geographical continuity of the land was obliterated by this tremendous deluge. Another of these great inundations occurred in 1570.

> A continued and violent gale from the northwest had long been sweeping the Atlantic waters into the North Sea, and had now piled them upon the fragile coasts of the provinces. The dykes, tasked beyond their strength, burst in every direction. The cities of Flanders to a considerable distance inland were suddenly invaded by the waters of the ocean.[2]

ORGANIC AND BIOCHEMICAL DEPOSITS

Limestone of biochemical origin.—In the case of non-clastic sediments variability in the rate of accumulation in different areas is probably as pronounced as it is in clastic sediments. There is little available data concerning the rate at which limestone sediments accumulate. But it is probable that a seasonal factor may become recognizable. The formation of limestones of biochemical origin is confined to rather definite geographical areas. Although sea water generally contains about 2,000,000 tons of calcium to the cubic mile[3] it is being extracted and built into rock formations within the confines of the tropics and subtropics in far greater quantities than elsewhere. The development of coral reefs, the formation of calcareous deposits by denitrifying bacteria and the lithification of shore deposits are the principal elements in the inequality of the distribution of calcareous sediments. The limitation of the action of each of these agencies to wide belts on

[1] J. L. Motley, *The Rise of the Dutch Republic*, Historical Introduction VI, Vol. I, p. 35 (London, 1913).

[2] *Op. cit.*, Vol. II, Part III, chap. v, pp. 285–87.

[3] John Murray, *Nature*, XXXIX (1889), 426.

either side of the equator strongly tends to confine the formation of considerable deposits of limestone to the tropical and subtropical seas.

Much has been accomplished in recent years toward delimiting the factors responsible for the areal limitations on limestone formations. The more recent work which has been done on the biochemical factors chiefly concerned in the formation of limestone has been summarized by Vaughan.[1]

In the Florida-Bahama region occur vast areas of chalky mud. These give place to non-calcareous sediments farther north. Dr. Vaughan's work on the Florida coast has shown that the bottom deposits now forming inside the Florida Keys varies from quartz sand to nearly pure calcareous ooze. He writes:

> Silica is abundant in the form of sand in the northern portion of Biscayne Bay, it becomes rarer toward the southwest and is present in small quantities as far as Big Pine Key. Toward the southwest as the silicious material becomes rarer, calcium carbonate becomes progressively more abundant, occurring as a flocculent sediment or ooze over practically the entire region from the lower portion of Biscayne Bay to the Gulf end of Florida Bay.[2]

The important discovery by the late Dr. G. H. Drew[3] of the part played by marine bacteria in producing chemical conditions favorable to the precipitation of calcium carbonate gave the first clue to the mode of origin of these incipient limestones of the Florida Keys. The environment considered especially favorable for these denitrifying bacteria includes a tropical or subtropical climate with "drainage into the sea of a well-wooded country composed of calcareous rock and the soluble organic calcium salts would be precipitated as calcium carbonate by the action of the bacteria."[4]

Coral reefs.—The contribution of corals to limestone formation is made chiefly in the form of fringing reefs some of which, like the Great Barrier reef of Australia, are several hundred miles in length.

[1] T. W. Vaughan, "Chemical and Organic Deposits of the Sea," *Bull. Geol. Soc. Amer*., XXVIII (1917), 933–44.

[2] T. W. Vaughan, "A Contribution to the Geological History of the Floridan Plateau," *Carnegie Inst. of Washington, Pub. 133* (1910), p. 119.

[3] G. H. Drew, *Year Book Carnegie Inst. No. 10* (1911), p. 125.

[4] *Ibid*., p. 139.

They occur also in detached masses called *chapeirões* on the coast of Brazil which Hartt described as follows:

> Corals grow over the bottom in small patches in the open sea, and without spreading much often rise to a height of forty to fifty or more feet like towers, and sometimes attain a level of low water, forming what are called on the Brazilian coast *chapeirões*. At the top these are usually very irregular and sometimes spread out like mushrooms, or as the fishermen say like umbrellas. Some of these *chapeirões* are only a few feet in diameter.[1]

Lithification.—Lithification of unconsolidated materials is a potent factor in permanently fixing on the seashore and bottom deposits of shifting sands, gravel, and other materials. Lithification of loose sediments by the deposition of Ca_2Co_3 is subject in a general way to latitude control. On the Atlantic coasts it is a relatively unimportant factor north of Florida on the American side and is seldom reported north of France on the European coast. The action of this factor on the coasts where it is common and important is highly irregular and as yet imperfectly understood. On the northeast coast of Brazil it has produced the curious wall-like reefs bordering the shoreline which have been described in detail by Branner.[2] Similar structures occur in the Levant which have been described by Lartel,[3] Hull,[4] and others. Beaufort[5] shows that the ancient port of Pompeiopolis in Asia Minor has been filled with dune sands which have become solidified on the beach of the port. This case, Branner notes, shows that the lithification has occurred within historical times.

At the island of Ascension Darwin found on the sea beaches immense accumulations of small well-rounded particles of shells and corals. At the depth of a few feet these were found cemented together into stone. These calcareous masses had been under

[1] C. F. Hartt, *Geology and Physical Geography of Brazil* (Boston, 1870), pp. 174–200.

[2] J. C. Branner, "The Stone Reefs of Brazil," *Bull. Mus. Comp. Zoöl.*, XLIV (1904), 1–285, pls. 1–83C.

[3] L. Lartel, *Exploration géologique de la Mer Morte de la Palestine* (Paris, 1887), p. 199.

[4] Edward Hull, *Mount Seir, Sinai, and Western Palestine* (London, 1889), p. 148.

[5] Francis Beaufort, *Karamania or a Brief Description of the South Coast of Asia Minor* (2d ed.; London, 1818), p. 249.

the observation of Lieutenant Evans for six years, who reported that there was an annual addition to them sometimes amounting to half an inch in thickness which began to deposit in October with the change in direction of the prevailing currents and which was later in the year in part re-dissolved by the waves.[1] This resolution of the calcium carbonate clearly indicates a seasonal factor in the formations of some limestones, deposition proceeding during only a portion of the year.

Variability of the Molluscan contribution.—The relative abundance of marine life on different parts of the sea bottom must be an important factor in the variation in rate of limestone accumulation in different areas. The general tendency of animal life to flourish best in shallow water is a well established fact. "Very many observations point to the conclusion that the density of life, both fishes and invertebrates, is greater on the sea bottom in close proximity to the land than in deeper waters farther out to sea. It is in such inshore waters that one finds the greatest wealth of animal life."[2] On the beach itself certain forms of marine life flourish in extraordinary abundance. At Fleshmick on the Isle of Man 2,940 individuals of *Balanaus balanoides* have been counted on one square foot of sea shore.[3]

In fresh-water lakes molluscan life is practically limited to depths less than 25 feet. Although a few fresh-water species have a bathymetric range much greater than this the contribution of such species to the calcareous element of lacustrine sediments is almost negligible. The bathymetric limitations of marine faunas are less abruptly drawn than those of fresh-water molluscan faunas, but they tend in the same direction, viz., toward a decrease in the amount of bottom life in deep water. It is evident from these facts that the molluscan contribution to limestone sediments would be largest along the inshore margin of the littoral zone. The seaward decrease seems to be somewhat irregular. This contribution

[1] Charles Darwin, *Geol. Observations* (1851), p. 49.

[2] James Johnson, *Conditions of Life in the Sea.* A Short Account of Quantitative Marine Biological Research (1908), p. 176.

[3] Catherine Maynie, "Marine Biology at Port Erin," *32d Ann. Rept.* (1918), p. 12.

is very considerable and varies greatly along different parts of the shore line. In one area a mussel bed may have a population of 16,000 molluscs to every square foot.[1] Another area may be practically barren of animal life. These barren areas occur in the tropics as well as elsewhere. Dr. Fred C. Baker[2] has called the writer's attention to a portion of the northeast coast of Brazil where molluscan life is extremely scarce.

The data which has been recorded in connection with oyster culture is instructive in connection with any consideration of the part which marine molluscs play in furnishing material for limestones. It is reported[3] that the oyster when introduced into a Louisiana area where it had been previously unknown yielded 1,500 to 2,000 bushels per acre in two years. In this particular case the shells of a single mollusc contributed an annual average thickness of about 4 inches of calcareous material over the whole of the bottom on which they lived. These figures will serve to illustrate the very different rates at which marine shells contribute to the materials for limestone formation. Along those parts of a coast where large prolific species like the oyster are dominant the calcareous element of the sediments must increase much more rapidly than where less prolific and smaller species make up the fauna.

An important factor in the accumulation of marine shells in any given area is the delicate adjustment to a particular kind of bottom environment which characterizes most marine molluscs. The way in which this adjustment would operate with the sand-loving cockle of the English coast has been aptly pointed out by Hunt.

> Were the supply of sand in Torbay to be cut off, another common feature in geology might meet with an illustration, viz., the sharply defined zone in which fossils frequently occur. Were such supply to be cut off (and from the isolated patches of red sandstones that skirt the bay we see how much less it already is than it has been in past time) the sand-loving cockles could not fail to be affected, and might even become extinct in this locality at a very rapid rate.[4]

[1] James Johnson, *op. cit.*

[2] Letter, June 12, 1912.

[3] Hugh M. Smith, *National Geographic Magazine,* XXIV (1913), 267.

[4] A. R. Hunt, "Notes on Torbay," *Rep. and Trans. Devonshire Association for the Advancement of Science, Literature, and Art,* X (1878), 186–87.

Bone beds.—A considerable portion of the fossil remains of vertebrate animals are found in "bone beds."

The term "bone bed" is in itself evidence of the tendency of vertebrate-fossil remains to accumulate in certain restricted zones and areas. Bone beds occur in each of the geological systems from the Devonian up. Even the few vertebrate remains which are known from the Ordovician may almost be said to represent a bone bed because of their abundance in a single zone. The Middle Devonian bone bed which forms the top of the Columbus limestone in Central Ohio is a representative Paleozoic deposit of this type. It has a thickness of 6 or 8 inches and consists of an "assemblage of millions on millions of generally imperfect but mostly recognizable organs or fragments of the bony structure of the forms of fish life most characteristic of the Devonian age."[1] This bed according to Stauffer[2] can be traced across the northern half of the state.

In the Upper Devonian shales of northern Pennsylvania occur numerous bone beds composed of the fragments of Catskill fishes. These beds of fish fragments are apt to vary from a few inches to a few feet in thickness and generally lie in the midst of beds which are barren.

The veteran collector C. H. Sternberg, who has probably collected more vertebrate fossils than any other living man, appears to have found the great majority of his fossils in bone beds. He states that

> all through the Belly River series of rocks are bone beds. In some places I secured hundreds, yes thousands of bones and teeth of many species, as well as shields of sturgeons and the enameled scales of gar-pikes as perfect as if picked up along a recent lake shore. There were also bones and shells of a great variety of soft shelled turtles and others, with beautifully sculptured shells; they range in size from less than six inches across to over two feet. Crocodile bones and the dermal or skin plates of plated dinosaurs were common. We secured hundreds of the pavement teeth of the ray Cope called *Myledaphus*, also countless vertebrae of the reptile *Champsosaurus*.[3]

[1] J. S. Newberry, *Monog. U.S. Geol. Surv.*, XVI (1889), 30.

[2] C. R. Stauffer, *Geol. Surv. of Ohio Bull. 10* (1909), p. 26.

[3] C. H. Sternberg, *Hunting Dinosaurs* (1917), p. 84.

C. M. Sternberg states that he knows of "no less than 7 bone beds in which only horned dinosaurs are represented."[1] Bone beds are frequently referred to in paleontological papers as "quarries." Concerning some of these quarries in Alberta Barnum Brown writes as follows:

> Frequently remains of many *Trachodonts* are found massed together in quarries, probably as a result of water action, in the Belly River and in the Edmonton strata, and there are two records of such occurrence in the Lance. In such quarries it is not exceptional to find *Trachodonts*, carnivorous dinosaurs, *Ceratopsia* and other remains commingled, although *Trachodonts* usually predominate.[2]

Various explanations have been offered for these aggregations of vertebrate remains, each of which is probably applicable to certain cases. Suffocation and burial by sand storms of the "frightened multitudes which had herded together in search of safety or courage" is a hypothesis offered by C. H. Sternberg.[3] Land vertebrates living in a wide alluvial plain might be periodically surrounded and herded together and drowned on the highest parts of an extensive area. In some instances prairie or forest fires may have been the compelling force which drove multitudes of land vertebrates into lakes and rivers. The fondness of most mammals for salt leads them, as is well known, to visit saline springs, and where these springs are in the midst of boggy ground may result in such aggregations of bones as those of the famous Bone Lick of Kentucky. Sir Charles Lyell[4] suggested still another way in which great numbers of large vertebrates may sometimes be drowned in lakes and rivers. He states that "It is well known that, during great droughts in the Pampas of South America, the horses, cattle, and deer throng to the rivers in such numbers that the foremost of the crowd are pushed into the stream by the pressure of others behind and are sometimes carried away by thousands and drowned."

[1] Letter to the writer, January 7, 1919.

[2] *Bull. Amer. Mus. Nat. Hist.*, XXXVII (1917), Art. X, pp. 282–84.

[3] Sternberg, *Life of a Fossil Hunter* (1909), p. 132.

[4] Sir Charles Lyell, *Travels in North America in the Years 1841 and 1842*, pp. 141–42.

Charles Darwin described a very curious habit of the guanaco or llama of South America which if shared by many of the extinct vertebrates may help to explain some of the bone beds of the Cretaceous and other rocks.

> The guanacos appear to have favorite spots for lying down to die. On the banks of the St. Cruz in certain circumscribed spaces, which were generally bushy and all near the river, the ground was actually white with bones. On one such spot I counted between ten and twenty heads. I particularly examined the bones; they did not appear as some scattered ones which I had seen gnawed or broken as if dragged together by beasts of prey. The animals in most cases must have crawled, before dying, beneath and amongst the bushes. Mr. Bynoe informs me that during a former voyage he observed the same circumstance on the banks of the Rio Gallegos. I do not at all understand the reason for this but I may observe that the wounded guanacos at the St. Cruz invariably walked towards the river. At St. Jago in the Cape de Verd Island, I remember having seen in a ravine a retired corner covered with bones of the goat; we at the time exclaimed that it was the burial ground of all the goats in the island.[1]

The periodic migration habit which characterizes many species of vertebrate animals tends strongly toward a highly irregular and localized distribution of their fossil remains. The migrating instinct which is remarkably developed in the majority of the birds of the temperate zone, in many species of fishes and in some of the mammals results in the great bulk of the species concerned dying in either its summer or winter habitat or in some especially hazardous portion of its semiannual journey. This habit is typically developed in the caribou of northwest Canada. The summer range and breeding ground of this deer lies several hundred miles to the north of its winter habitat. The number of individuals which move south each autumn from the Arctic barrens to the forested lake region of north central Canada numbers hundreds of thousands if not millions of individuals.[2] The bulk of the herds follow certain well-defined routes and generally cross certain east to west trending lakes at certain points. If we consider the thousands of years that this movement has been going on and the frequent casualties which have probably occurred in crossing on the new

[1] Charles Darwin, *The Voyage of the Beagle*, p. 172.

[2] E. M. Kindle, "A Note on the Migration of the Barren Ground Caribou," *Ottawa Naturalist*, XXXI (1917), 107–9.

autumn ice at points like Fond du Lac and Fort Rae on Great Slave Lake, we will see how at certain such points in the lakes and in the bogs which lay near the routes of migration the bodies of numberless caribou may have been entombed while other lakes and bogs remote from the north and south routes of migration might be entirely free from such remains.

Some species of animals which do not possess the seasonal migration instinct are subject to waves of migration which recur at irregular intervals often separated by two or more decades. Such waves appear to be caused by an excessive increase in the numbers of a species within its normal habitat. The rapid-breeding Siberian lemming is subject to these migration waves. Dr. Brehm[1] vividly describes the way in which impending famine starts an exodus from an overpopulated tundra.

> Famine threatens, perhaps actually sets in. The anxious animals crowd together and begin their march, hundreds join with hundreds, thousands with other thousands, the troops become swarms, the swarms armies. They travel in a definite direction at first following old tracks, but soon striking out new ones; in unending files—defying all computation—they hasten onwards; over the cliffs they plunge into the water. Thousands fall victims to want and hunger; the army behind streams on over their corpses; hundreds of thousands are drowned in the water or are shattered at the foot of the cliffs; the remainder speed on; other hundreds and thousands fall victims to the voracity of Arctic and red foxes, wolves and gluttons, rough-legged buzzards and ravens, owls and skuas which have followed them; the survivors pay no heed.[2]

The famine crazed hordes of migrating individuals which may result when a species greatly outbreeds the food possibilities of its habitat have probably furnished important contributions to the fossil bone beds of previous epochs as they are doing to those of the present.

Phenomenal increase in the animalcule life of fresh and salt water sometimes results in the pollution of the water and destruction of all the life in it. The oldest recorded example of this kind is probably the biblical one of the Egyptian plagues when the water of the Nile was as it were "turned to blood and all the fish died."[3]

[1] A. E. Brehm, *From the North Pole to the Equator*, p. 79.

[2] R. F. Scharff, *The History of the European Fauna* (1899), pp. 139–40.

[3] Exodus 7:20, 21.

The extraordinary abundance of flagellate animalcules is reported[1] to have caused red water for 200 miles along the coast of California and produced by their decomposition the death of shoals of fish and quantities of other marine animals. Phenomena of this kind must cause the sudden deposition on the sea bottom of unusual and extraordinary quantities of the remains of pelagic life of various kinds. If great numbers of fishes or other vertebrate animals were affected a bone bed might result.

Displacement of ocean currents.—Still another cause of discontinuity in the accumulation of marine fossils over extensive areas is to be found in the occasional shifting or displacement of ocean currents from parts of their usual routes by great storms. Professor Verrill encountered a striking example of this class of phenomena several years ago while dredging under the edge of the Gulf Stream, southeast of Long Island.

> One of the most peculiar facts connected with our dredging this season was the scarcity or total absence of many of the species especially of *Crustacea*, that were taken in the two previous seasons, in essentially the same localities and depths in vast numbers—several thousands at a time. . . . . An attempt to catch the "tile-fish" (*Lopholatilus*) by means of a long trawl-line on essentially the same ground where eighty were caught on one occasion last year, resulted in a total failure this year. It is probable, therefore, that the finding of vast numbers of dead tile-fishes floating at the surface in this region last winter, as was reported by many vessels, was connected with a wholesale destruction of the life at the bottom, along the shallower part of this belt (in 70 to 150 fathoms) where the southern forms of life and higher temperatures (48° to 50°) are found. This great destruction of the life was probably caused by a very severe storm that occurred in this region at that time, which by agitating the bottom-water forced outward the very cold water that even in summer occupies the great area of shallower sea in less than 60 fathoms along the coast, and thus caused a sudden lowering of the temperature along this narrow warm zone where the tile-fish and the crustacea referred to were formerly found.[2]

Barren areas.—Certain areas in many seas appear to remain permanently almost entirely barren of life though surrounded by areas crowded with marine life. One of the reasons for such barren

[1] *The Library of Natural History*, III (1906), 768.

[2] A. E. Verrill, "Evidence of Great Destruction of Life Last Winter," *Amer. Jour. Sci.*, XXIV (1882), 366.

areas in the case of sandy bottoms is doubtless the tendency of sands to move rapidly under current action and smother the marine life which attempts to live on them. Dr. G. A. Huntsman, who has been engaged in studying the conditions under which marine animals live in the Gulf of St. Lawrence has directed attention to another factor in producing lifeless zones. He states:

> By means of these traps we discovered that a barren zone existed off the Cape Breton shore, comprising the part of the sloping bottom between the depths of 10 and 20 fathoms. In this zone the temperature at the bottom underwent violent fluctuations, often in the course of a day or so, at one time being as high as 65° F., and at another as low as 39° F. This was caused by the winds, for when the wind was blowing on-shore it drove the surface water against the coast and heaped it up forcing the deeper colder water down; then when it changed and blew off-shore the warm surface water was driven away from the coast and the cold water welled up from below to take its place, and so flooded the zone. The effect of this on the slow moving bottom animals may be imagined. Few of them would be able to stand such changes, but the active fishes are able to move up and down the slope and avoid these changes.[1]

Seasonal variation.—Another factor in the variation in the rate of sedimentation in the sea is the seasonal factor. The annual seasonal changes in the sea result in marked differences in the amount of organic materials deposited on the sea bottom during different parts of the year. The registration of seasonal changes by banding in the volume of clastic sediments in aqueoglacial deposits has been exhaustively discussed by Sayles.[2] Comparable with the great contrasts in the volume of lacustrine sediments deposited during different parts of the annual cycle are the different amounts of organic materials which the plankton life of the sea showers on the bottom in winter and in summer. It is possible that we may yet be able to interpret some of the fine lamination in sea-laid deposits in the precise terms of years. "In early spring there is a great awakening in the oceans comparable with the growing of the grass and the budding of the trees on land." This awakening corresponds to the time when the alkalinity of the sea is at a maximum.

[1] *Canadian Fisherman*, May, 1917.

[2] R. W. Sayles, *op. cit.*

Prof. Benj. Moore discovered that the sea around the Isle of Man was a great deal more alkaline in spring (say April) than it is in summer (say July); and then on examining monthly samples taken throughout the year he was able to show that the alkalinity which gets low in summer increases somewhat in autumn, then decreases rapidly during the winter, and after several months of a minimum begins to increase again in March, and rapidly rises to its maximum in April. That is the periodic change of alkalinity and it will be seen to correspond roughly with certain very important changes in the living microscopic contents of the sea and the connection between the two may be made out by inquiry into the nature and meaning of the changes in alkalinity. The alkalinity of the sea is due to the relative absence of carbon dioxide. . . . . We find that at Port Erin in March the water, not only on the shore, but also out in the open sea, is acid to phenolphthalein, while a month later it is distinctly alkaline to the same indicator and this change signifies an enormous conversion of carbon in the inorganic into carbon in the organic form, a turnover of such extent that it probably amounts to 20,000 or 30,000 tons of carbon per cubic mile of sea-water. . . . . Or we may imagine this same quantity of carbon as forming the bodies of all the organisms found in the sea all around the shores of the Isle of Man, in which case the 300,000 tons would be distributed through the zone of water extending to about one mile out from the shore and down to an average depth at that distance of, say, ten fathoms. Now all of these organisms have obtained their carbon from the carbon dioxide present in the sea-water in spring and it is absolutely certain that in the absence of this abundant supply of available carbon-food, the millions and millions or organisms in question could never have existed." . . . . "Practically all our food-fishes in the sea, except the herring, produce their eggs in winter or early spring. They are hatching out in vast quantities during the time that the alkalinity is rapidly increasing and the phytoplankton of diatoms is daily growing in amount."[1]

It is evident that the vast increase in the quantity of marine life during the spring and summer must be registered in sea-bottom deposition by a corresponding increase in the amount of diatom and other organic materials dropped on the sea bottom. We have therefore throughout the seas of the temperate and northern parts of the earth annually a summer period of maximum sedimentation following a winter period of minimum sedimentation.

CONCLUSIONS

The evidence appears to be distinctly against uniformity in sedimentation. Biologists in recent years have generally accepted

[1] W. A. Herdman, "Some Periodic Changes in Nature," *32d Ann. Rept. Liverpool Marine Biology Committee* (1918), pp. 23, 24, and 27.

the relatively new conception of succession as a process which results inevitably from the activities of each plant or animal community destroying by its own activities the possibility of indefinitely continued existence in the same place. The operation of this and other factors, some of which produce more sudden results, tend inevitably to vary the rate and shift the area of accumulation of the organic constituents of sediments. In a comparable manner sedimentation sets its own time limit on its operation in any given area. Alluviation terminates automatically when the deposits of a valley reach a thickness corresponding to the height of the maximum flood waters of the valley. Sedimentation ceases in a lake when the deposits approximate the lake surface. Although this familiar conception of the self termination of terrestrial sedimentation in fluvial and lacustrine waters has been generally recognized and applied to terrestrial sediments it has not been extended to marine conditions. But its application though less obvious is almost equally justified. In foreland structures the building of coarse deposits of sand, gravel, and shingle is limited vertically by the height to which wave action reaches. Horizontally the direction and strength of currents are the chief limiting factors. When these rather definite limits have been reached by a particular spit its supply of sediments goes elsewhere.

In areas remote from the shore line wave base and current action are determining factors in sedimentation. Wave base differs for different classes of materials as pointed out by Barrell.[1] It is deeper for fine than for coarse materials. Mud deposits can never build to the surface in the open sea because of the dissipating influence of the waves. Sand deposits fed by an abundant supply may, however, reach the surface. Whatever the upper limit of a particular formation may be, it will depend on the interplay of wave and current action, and when reached the further growth will be lateral or else diverted to a new area by a shifting of the flow of materials. Any adequate conception of marine sedimentation must include numerous great river-like currents some with intermittent activity, others periodic, while a few doubtless follow

[1] Jos. Barrell, "Rhythms and the Movement of Geologic Time," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 778.

permanent routes in the sea bottom. Many of these probably move the finer sediments toward and over the border of the continental shelf as definitely as terrestrial streams move their sediments toward the sea.

Geologists and paleontologists may learn much regarding the rôle of marine currents from the keen analysis of living faunas which such investigators as Peterson are making. This author who has discriminated and mapped several sharply contrasted bottom faunas in the Skagerrak and Kattegat finds that

> The *Modiola* epifauna occurs especially where there is a strong current close to the bottom, clearing away the finer particles so that stones and shells lie exposed, affording sites for attachment for the *Modiola*, which may here occur in such numbers as entirely to cover the bottom (see Pl. IX) for great tracts in the current channels.[1]

The inferences which we can at present make concerning some of the conditions controlling marine sedimentation are based on such detached bits of evidence as have been brought together in this paper. It is hoped, however, that it will soon be possible to base conclusion relating to such problems on intensive studies of numerous selected areas of sea bottom in which areal mapping of bottom deposits will be an important feature.

[1] C. G. Joh. Peterson, "The Sea Bottom and Its Production of Fish Food," *Rept. Danish Biol. Sta. to Board of Agriculture* (1918), p. 15.

SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE PRE-CAMBRIAN OF NORTHERN QUEBEC

H. C. COOKE

PART IV

DIASTROPHISM

The evidence cited in the preceding pages indicates that previous to the end of the period of deposition of the Mattagami series no general orogenic movements took place in this region, but that such movements as occurred were of the gentle, epeirogenic type. After the deposition of the Mattagami series, intense orogenic movements went on, which folded the Mattagami and Nemenjish series and the Abitibi volcanics closely, and converted a large proportion of them into schists. By some writers this folding has been supposed to have accompanied the intrusion of the granite, and been caused by the hydrostatic pressure of the upwelling magma. Were this the case, the remnants of the older series should have dominantly synclinal or monoclinal structures, and there would be no general correspondence between the axes of the folds of the different remnants. Such a condition appears to obtain in the Grenville-granite complex in the Adirondacks, according to W. J. Miller.[1] However, it does not appear to be the case throughout Ontario and Quebec, where no dominantly synclinal or monoclinal structure exists, and where there appear to be a definite subparallelism of the axes of folding over considerable areas.

A tabulation of the areas which have been discussed, with their general structure and the strike of their axes of folding as nearly as determinable, is given on page 368.

The parallelism of the axes of folding of the different, rather widely separated areas is remarkable. All, it will be observed, fall within between N. 75° E. and S. 70° E. As the folds are

[1] W. J. Miller, *Jour. Geol.*, XXIV (1916), 587.

probably to be considered only as secondary folds on the flanks of the large regional major folds, parallelism is not to be expected between them, as the strike of the axes of such secondary folds is governed by the general strike of the strata at the point where they occur. The extension of data of the foregoing type over a large region will enable the nature of the great regional folds to be worked out; but this cannot be done now, as the area under discussion, though large, is small compared with the size of the Labrador peninsula.

Area	Structure	Strike of Axis
Kenoniska	Anticline	S. 75° E.
Lucky Strike	Anticline	S. 75° E.
Brock	Anticline	N. 85° E.
Opawika	An-Sy-An	N. 75° E.
Father's Lake	Syncline	S. 75° E.
Windy Lake	Monocline	E.-W.
Nemenjish	....	N. 60° E.
Eau Jaune	....	S. 70° E.
Mattagami	Probable anticline	N. 80° E.
Pontiac	Probable anticline	E.-W. E.

The general parallelism of axes indicates that the regional folding was not caused by the hydrostatic pressures of batholithic intrusions, but by a compressive stress affecting large areas uniformly; while the lack of shear in the granites shows that the folding occurred before their intrusion. This conclusion does not of course invalidate the possibility that the intrusions followed the folding very closely.

The folding may therefore be dated as post-Mattagami and pre-batholithic. It resulted in the formation of close folds with an east-west axial trend and cross folds of a much more open type. The cross folding has given a plunge of some 20° to the axes of the major folds.

In addition to the post-Mattagami folding movement, some evidence exists that there was an earlier folding, affecting not the region under discussion, but that to the south, the borders of the continental segment, in Grenville time. This accompanied or closely followed the intrusion of the earlier granite, but preceded the intrusion of the anorthosite. In the Adirondacks, Cushing,[1]

[1] *Reports of the New York State Museum.*

Kemp, and Smyth describe the Grenville series and older granite-gneiss as much more metamorphosed than the intrusive anorthosite, a fact which may indicate an early folding, but may also be due to the greater competence of the anorthosite to resist the later folding. The evidence is slight, but it is very possibly the case that the marginal intrusion of granite accompanying the uplift of the Grenville continental segment at the close of Grenville time was accompanied by marginal folding movements. If this is true, we should expect to find in these districts the equivalents of the Mattagami series resting with structural as well as erosional unconformity on the Grenville. This seems to have been the condition in the Madoc district, where according to Miller the Hastings series, a possible equivalent of the Mattagami series, rests against the upturned edges of the Grenville.[1]

GRENVILLE (?) SEDIMENTS ON THE WEST SIDE OF HUDSON BAY

While no sediments that can be definitely asserted to be of Grenville age have as yet been described to the west of Hudson Bay, it is interesting to note that there are a number of areas of rocks whose petrography is similar to that of the Grenville series, and which, like them, are intruded by granite apparently of very great age. The reports of Tyrrell and others in this region have yielded a number of more or less doubtful occurrences of these rocks. A few others have been described to the writer by present members of the staff of the Geological Survey. In the vicinity of Lake La Ronge, W. McInnes has reported[2] crystalline limestones and basic intrusives, greatly folded and altered, and intruded by the granite gneisses of the district. E. L. Bruce has informed the writer that he found ancient garnet and staurolite gneisses intruded by granites around Wekusko Lake, Manitoba. One of the gneisses analyzed is undoubtedly of sedimentary origin. Tyrrell, studying this same area, reports that this gneiss "grades downward into the greenstone schists"; apparently indicating a conformable relation between the two, similar to that described in this paper. F. J. Alcock states that to the northeast of Lake Athabaska he found an

[1] *Rept. Ont. Bur. of Mines,* Part 2, 1914, p. 12.

[2] *Geol. Surv. Can. Mem. 30,* 1913, p. 48.

area of garnetiferous mica gneisses, intruded by granites. The occurrence of such sediments is of great interest, as indicating the possibility of future correlation with the eastern side of Hudson Bay.

THEORETICAL CONSIDERATIONS

Conditions of Extrusions of Abitibi Volcanics

The nature of the floor upon which the Abitibi volcanics were poured out cannot be more than a matter for conjecture. No trace has as yet been found of the rocks which once composed it, to show whether they were sedimentary or igneous, flat-lying or folded. Other facts are, however, more certain.

In the following section the conclusion is drawn from a consideration of the nature of the Grenville sediments that the Grenville series in the interior of Quebec was deposited under continental or shoal-water marine conditions. The region was therefore a continental plateau, or positive element, even at this time. As evidence is lacking of the occurrence of any great earth movement between the extrusion of the Abitibi volcanics and the deposition of the Grenville series, it would be reasonable to conclude that during the extrusive period also the region must have been a positive element. Some direct evidence on this question is obtainable from the lavas themselves, using pillow lavas and bedded tuffs as criteria of subaqueous extrusion.

On Obatogamau Lake all the lavas, even the basal basalts, show pillow structures. On Kaopatina Lake and eastward to Father's Lake, the basalts are not pillowed, but the overlying lavas have the structure well developed, and interbanded tuffs are well bedded. On Tush Lake and the areas to the northward, none of the lavas are well bedded. While this line of evidence has not been worked out in detail throughout the entire area, the facts obtained suggest that the extrusive period was one of gradual submergence. The earliest recognized shore must have lain between Obatogamau and Kaopatina lakes, and a westward transgression of the sea took place thereafter. The submergence evidently went on after the extrusion of the lavas was complete, since garnetiferous gneisses

identical with the rocks of the Grenville series are found up to the shores of James Bay.

Alternative to the hypothesis of marine transgression lies the possibility that at this time the land was covered by a series of large lakes. If the land remained above the level of the sea, the outpourings of lava that took place must have filled the stream valleys and utterly disorganized the drainage; lakes must have been formed as a result, and if the region was one of low relief, as it will presently be shown appears probable, these lakes may have attained sizes comparable to those of the great glacial lakes of Pleistocene times. Such a condition would explain the facts stated, as well as marine transgression.

Topographically, the surface on which the lavas were poured out seems to have been one of low relief. Had high mountains existed at the time, the remains of the peaks, around which the lavas would have flowed, should surely be found now penetrating into at least the lower beds above, which are now on edge. Nothing of the sort has come to light. Again, had the extrusions been thrown out from high peaks, such as the volcanic cones of the present day, we might now expect to find sudden changes of strike near the volcanic centers, due to the occurrence of steep depositional dips. This has not been observed. The conclusion may therefore tentatively be drawn that the flows were extruded as fissure eruptions, at least in the case of the more widely distributed basic lavas, and to have flowed out over a surface of fairly low relief. More detailed field work is necessary, with careful mapping of the areal boundaries of separate flows, to establish this conclusion.

Conditions of Deposition of the Grenville Series

Areal distribution.—A careful search has been made of the reports of the explorers of northern Quebec and Labrador, and determinations made from their descriptions of the location of areas of the Grenville series, using as criteria for its determination mainly petrographic similarity and geological relations. Many descriptions were met with of rocks which bear a strong resemblance to certain phases of the Grenville, but are likewise indistinguishable from the Pontiac or some other highly altered sedimentary series.

These are not included on the accompanying map; the bodies mapped are confined to those highly garnetiferous types, with or without limestone, which are peculiarly characteristic of the

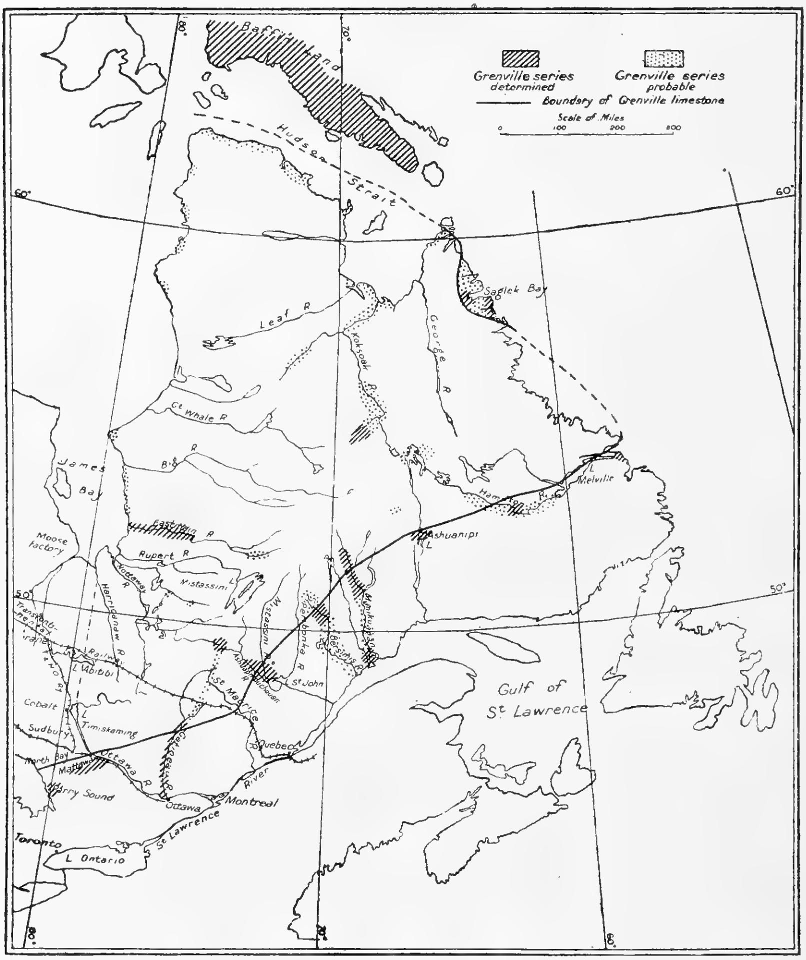

FIG. 13.—Map to illustrate the distribution of the limestone member of the Grenville series. Limestone is absent on the Hudson Bay side of the heavy black line and present on the southeast side.

Grenville. The areas shown on the map (Fig. 13) are those in which the amount of the Grenville series present is so large and its

characteristics so definite that its identification can scarcely be doubted. The dotted patches are those in which the amount of Grenville present, relative to that of the granite which has intruded it, is small, so that its identification is more open to argument. Even in these cases, however, the effort has been made, as stated, to weed out the doubtful cases and include none but those in which identification is fairly certain. The results show the presence of the Grenville over the whole interior of the Labrador peninsula, wherever exploration has been carried, as well as in Baffin Land and the long-known districts to the south.

The study of the older reports, together with the writer's own field work, has brought to light a peculiarity in the distribution of the limestone member of the series. Limestone is found in Baffin Land, in places along the Labrador coast, and throughout southern Quebec and Ontario, as well as in the Adirondack region; but little or no limestone has been described throughout the interior plateau of northern Quebec. It has been considered by certain authors that the lack of limestone in this region is due to its solution by the intrusive granite, where the granite is present in sufficiently large amount. This opinion does not appear to be well founded. In the section northward along the Gatineau River, above the town of Maniwaki, the writer found that the limestone member decreases in relative amount, with corresponding increase of the clastic members of the series, until it disappears altogether, without any notable increase in the amount of intrusive granite which is present throughout in considerable amount. In the Nemenjish area, there are at least several hundred feet of clastics, entirely free from intrusive granite. With them there are interbedded only two bands of limestone, each about a foot in thickness. These facts seem explicable only on the hypothesis that the limestone never was deposited in the localities mentioned; in other words, the lack of limestone in certain areas is due mainly to a primary difference of sedimentation rather than to removal after deposition by the granite. A preliminary attempt has been made, from a study of the reports, to determine the position throughout the Labrador-Quebec region at which this change in sedimentation took place, and to indicate it on the map (Fig. 13) by a heavy black line. On the Hudson Bay side of this line little or

no limestone has been found, but on the other side of the line limestone in considerable amount.

The existence of such a definite boundary is of great significance in considering the conditions of deposition of the Grenville series. We have an interior region in which, for some reason, conditions were unfavorable for the deposition of limestone; while, beyond the margins of this region, limestone was deposited freely. Two possibilities present themselves to explain this fact. The portion of the Grenville within the limestone boundary may be of terrestrial origin, in which case the limestone boundary will represent approximately the location of the Grenville shore line; or the whole series may be marine, but the clastic sediment within the limestone boundary may have been so abundant that limestone was not formed there. In either case the limestone boundary represents a topographic break, where an interior plateau fell off sharply to a lower level. The solution of this problem therefore depends on the determination of the marine or non-marine origin of the Grenville sediments within the limestone boundary.

The data at hand are not sufficient for the solution of this problem, since the comparatively small Nemenjish area is as yet the only one which has been studied. The known facts, pro and con, may be summarized as follows:

A. In favor of a non-marine origin of the series where limestone is absent:

1. The Nemenjish sediments as a rule have the composition of an altered greywacke as if derived from older rocks by disintegration without much decomposition. They show small variations in mineral composition, but these variations appear to be due to variation in the composition of the older rocks from which they were derived, rather than the variations due to normal weathering and consequent separation into sandstone and shale constituents. True quartzites, shales or slates, and limestones are conspicuous by their absence, or their presence in very small amount, in the northern region, although they are present in greater amount in the marine division of the series beyond the limestone boundary—a natural result of transportation over greater distances.

2. Although remnants of the Grenville sediments appear to be scattered over the whole of the Labrador plateau, it is not yet proved

that they once formed a continuous sheet over this area. It is equally possible that they may have been deposited in discontinuous basins.

3. If the origin of the sediments was marine, a study of the map shows that it will be necessary to postulate that the land area from which they were derived occupied part of the present area of Hudson Bay. It is difficult to conceive of the transport of sandy sediments from a land area in this position to the eastern Ontario district or the Labrador coast.

B. In favor of a marine origin:

1. The entire lack of conglomerates or coarse-grained clastic sediment in the known portions of this series is strongly against the hypothesis of a non-marine origin. Deformation has not been so great as to destroy such textures, as their preservation in the Mattagami series shows.

2. In the Nemenjish area all the rocks are well bedded, usually in beds twenty or more feet in thickness. No trace remains of cross-bedding, lens-shaped beds, or other structures characteristic of terrestrial deposits. This area might of course have been part of the site of a large lake.

3. The greywacke-like composition of the rocks might equally well be explained on the basis of the lack of vegetation in these early times, so that the composition might not argue either for or against the marine origin. Where vegetation was lacking and precipitation abundant, sediment would be removed as fast as disintegration took place, so that complete decomposition of the rock constituents by weathering might not have taken place.

Conditions of Deposition of the Mattagami Series

Areal distribution.—The Mattagami series is not known certainly outside of the region under discussion, as its existence and age relations have been recognized only within the last few years. Apparently, however, it was once fairly uniformly distributed over northwestern Quebec, at least as far north as the East Main River, where sediments of similar composition and degree of deformation are described by Low.[1] The writer has not been able to identify the

[1] *Geol. Surv. Can., Ann. Rept.*, VIII (1896), Part L.

series elsewhere in northern Quebec from the reports. The Timiskaming, Sudbury, and Hastings series to the south and southwest may possibly be of the same age, though a definite correlation cannot now be made.

The same difficulties obtain in the Mattagami series as in the Grenville series with regard to a marine or non-marine origin. Generally speaking, the composition of the two series is very similar, that of an altered, rather impure sand, implying conditions of rapid weathering and deposition without extended decomposition of the rock constituents. All the arguments for and against a marine origin that have been previously cited in the case of the Grenville hold also in the case of the Mattagami series, with the exception that the Mattagami series includes a heavy basal conglomerate of such thickness that a non-marine origin for this member at least seems very probable. In the Lucky Strike area, where the series has been greatly thinned by shearing, the present thickness of the conglomerate band is approximately 300 feet. In the Kenoniska area there are two bands of conglomerate, separated by a thick, massive, basic greywacke, with very little trace of bedding and holding an occasional pebble. The thickness of the whole is very difficult to estimate on account of the probable thickening of the formation at the nose of the fold by flowage, and uncertainty as to the plunge of the fold. A minimum estimate by the writer, however, yielded a thickness here of at least 1,000 feet. According to Barrell, marine conglomerates are rarely over 100 feet in thickness. If this is true, the conglomerate member of the Mattagami series is probably of non-marine origin.

Diastrophism

Certain considerations seem to indicate that the great diastrophic movements which followed the deposition of the Mattagami series were connected with, or resulted in, the primary formation of the great geosyncline of Hudson Bay. These may be summarized as follows:

1. If the Nemenjish and Mattagami series are considered to be marine formations, their distribution indicates that the only possible land mass which would supply the necessary sediments must have occupied the present position of Hudson Bay.

2. Leith[1] has shown that the formation of the great Lake Superior syncline began in pre-Keweenawan time, and suggests indirectly that it may have begun to form very much earlier, even in the pre-Huronian. The formation of a structure of this size must have been accompanied by profound deformative effects on the rocks for a long distance to the north and south. The evidence from the parts of northern Ontario and Quebec dealt with in this paper indicates that they have been affected by only one intense folding movement of pre-Keweenawan age, the post-Mattagami movement. The Bruce series, or Lower Huronian of the north shore of Lake Huron, and the Cobalt series which overlies it, where not affected by Keweenawan deformation are only gently folded and rest on a folded and peneplaned surface. It seems reasonable therefore to correlate the post-Mattagami folding with the primary formation of the great synclines of Lake Superior and Hudson Bay. The region between, under this hypothesis, is an anticlinorium, and was probably mountainous, so far as can be judged from estimates of the thicknesses of rock removed during the pre-Huronian peneplanation.

3. The Nastapoka sediments on the east shore of Hudson Bay are classified by Leith[2] as of Keweenawan age, with perhaps some Animikee rocks included. The presence of these rocks shows that at this time Hudson Bay was already a synclinal depression in which sediments were being deposited. Their deformation shows, in addition, that the folding movements by which it was formed were still going on. This history is parallel to that of the Lake Superior basin, the deformation of which continued throughout pre-Cambrian time up to the end of the Keweenawan.

REGIONAL HISTORY

In the earliest times of which we have record the northern Quebec region appears to have been a continental plateau of low relief. This plateau included not only northern Quebec, Labrador, and probably Hudson Bay, but also Baffin Land, eastern Ontario, parts of New York and Vermont, and perhaps a large area to the

[1] *U.S. Geol. Surv. Monograph 52* (1911), p. 622.

[2] *Economic Geology*, V (1910), 227–46.

west and southwest of Hudson Bay. What its further extent may have been is not known. The nature of the rocks that composed the plateau and formed the floor on which later rocks were laid down is yet unknown. The first event of which record remains is the extrusion of vast amounts of lavas, which spread in sheets over the greater part of it. Many of these lavas possess pillow structures and are interbanded with beds of tuffaceous sediments. Both of these lines of evidence indicate subaqueous extrusion; so that either the sea covered portions of the plateau at this time or the earlier extrusions of lava so disorganized the drainage as to create large lakes, in which ellipsoidal lavas and bedded tuffs were laid down. In the northern Quebec district the oldest lavas found are of basaltic composition. They were succeeded by more acid types as extrusion went on, so that the basalts are overlain successively by porphyritic basalts and andesites. Between the andesite flows, beds of chert are occasionally found, which probably represent portions of the load of magmatic waters accompanying the flows. Near or at the top of the andesite flows, beds of coarse tuff are found locally, indicating that the period of andesite extrusion ended with volcanic explosions. The period of volcanism closed with a number of local and small extrusions of quartz porphyry. In places this porphyry forms a breccia instead of a massive flow. The brecciated texture has been shown to be due porbably to subaqueous extrusion, and thus corresponds to the pillow structure in the more basic lavas.

At the close of the extrusive period deposition of sediments began. The lowest beds are of a rather basic, tuffaceous composition. These beds soon give place to others which have more the composition of impure sands and are now altered to micaceous schists containing a few garnets. Higher in the series a further change in composition takes place, probably by an increase in the lime content of the beds, which is marked by the appearance of garnets in great numbers. Interbedded with the garnetiferous mica gneisses are beds of garnetiferous hornblende gneiss and an occasional thin bed of crystalline limestone. These sediments, locally termed the Nemenjish series, are correlated with the Grenville series. It is as yet uncertain whether they are to be con-

sidered as of marine or of terrestrial origin. They are separated by a fairly sharp boundary from the known marine portion of the Grenville to the south, in which much limestone is found. This boundary represents approximately the position of the ancient shore line, if the sediments to the north are of terrestrial origin; if the sediments to the north are marine, it represents a topographic break, separating an area of very shoal water deposition to the north from an area of deeper water deposition to the south. In the latter case, the sediments of the Grenville must have been derived from a land area occupying the site of Hudson Bay.

At the end of the Grenville period of deposition, uplift appears to have taken place, and a period of erosion ensued. This was sufficiently long to remove all or the greater part of the Grenville series from much of the interior plateau, where presumably it was thinnest, since in the area between Lake Mistassini and James Bay the supposed Grenville has been found in only two places between the lavas and the Mattagami sediments.

The emergence just described appears to have been accompanied or closely followed by intrusions of granite in the southern portions of the plateau. This "older granite" has not yet been recognized farther north than Lake St. John. There is some evidence to show that folding movements also accompanied these granite intrusions, causing deformation of the rocks of the southern edge of the plateau. After the intrusion of the granite and the folding movements, if any, were ended, masses of anorthosite and feldspathic gabbro were intruded. These have been found as far north as Lake Chibougamau, but are more numerous and larger in the southern districts, where the earlier granite occurs. The localization of two such widespread intrusions within similar limits is probably due to some common cause; perhaps to the presence of lines of weakness in the older rocks caused by the folding just mentioned. No important orogenic movement appears to have accompanied the anorthosite intrusion.

The next event in the history of the region was the deposition of the Mattagami series, which may or may not have been accompanied by marine submergence. The thickness of the basal conglomerate of the series indicates that at least this member probably

accumulated under non-marine conditions, if Barrell's conclusion as to the thickness of marine conglomerates is to be accepted. The deposition of the conglomerate was followed by that of thick beds of arkose and greywacke, locally with a little quartzite. A limestone member may have been present in beds laid down beyond the southern margin of the interior plateau.

Following the deposition of the Mattagami series came a period of intense orogenic movement and mountain-building, during which all the rocks were folded closely along east-west axes and gently along north-south axes. The more incompetent rocks were converted into schists. Following the folding was the great intrusion of later granite, which stoped away and digested vast quantities of the older rocks, and which, now exposed by erosion, underlies the major part of the region.

A period of erosion followed, so long that the mountains of the last folding were cut down nearly to base-level, and the granite batholiths laid bare. No recognizable trace has yet been found of the sediments which resulted from this erosion and which must have been deposited somewhere during this period. The next event of which any record remains is the deposition of the Bruce series on the peneplained surface of the older rocks on the north shore of Lake Huron. This indicates a third period of submergence, which appears, however, to have been of small areal extent. Emergence and the erosion of about 1,600 feet of the Bruce series followed, with further gentle folding, after which a more extensive submergence initiated the deposition of the Cobalt series. At this time the sea transgressed certainly as far northward as Lake Abitibi, and possibly to Lake Mistassini and beyond. The nature of the Cobalt sediments indicates that the sea was probably very shallow. Glacial conditions obtained at this time, according to Coleman, M. E. Wilson, and others, and influenced the character of the sediments laid down. The final event in the history of the region, so far as traced here, was the intrusion of gabbro and diabase into the older rocks in sills and dykes, preceding or accompanying further gentle folding movements.

Climate and life.—Our knowledge of the climate and life conditions that prevailed in these early times is exceedingly scanty,

and all of it so inferential that it is of small value. The presence of the great thicknesses of limestone in the Grenville series is, however, strongly suggestive of the existence of lime-precipitating organisms even at that early period, although it is of course conceivable that the precipitation of lime at that time may have been chemical. The common presence of scales of graphite in the quartzite and crystalline limestone and the also common presence of H_2S apparently included in the limestone crystals are, however, both rather strongly corroborative of an organic origin. Whether life extended to the land at this time is more doubtful. If it did, it must have been of a very sparse nature, with little restraining effect on the movement of soils under erosive influences. The nature of the clastic sediments that were deposited throughout Grenville and Mattagami time indicates conditions under which the soil was removed from the land surfaces without the prolonged weathering and thorough decomposition of the mineral constituents that a good covering of vegetation promotes.

The climate of the Grenville period may be inferred to have been mild for the following reasons: (1) If the limestone of the series is of organic origin, it would imply the existence of a warm epicontinental sea. (2) The Grenville sediments, though not well weathered, are as a rule much more acid than the basic lavas from which in all probability they were largely derived. This would indicate, in the absence of vegetation, a warm climate favoring the rapid decomposition of the rock constituents. (3) The enormous extrusions of lava which took place preceding the deposition of the Grenville must have been accompanied by the exhalation of huge volumes of carbon dioxide into the atmosphere. The presence of this carbon dioxide may have had some effect in ameliorating the climate of the period.

The climate during the Mattagami period is more in doubt, but it was probably cooler than that of the Grenville period. The presence of limestone in very small quantities only might suggest a sea colder than that of Grenville time, in which lime-secreting organisms did not exist in such profusion. The clastics, though frequently similar to the Grenville, are in general more basic and less weathered. This might also indicate colder climatic conditions.

SUMMARY

This paper first describes methods which the writer has used for the determination of structure in the volcanic flows, often termed "Keewatin," that form the oldest known rocks of northern Quebec. These methods, applied to four areas of these volcanics on the Opawika River, a tributary of the Nottaway, have resulted in the determination of a similar sequence of extrusion in each area. The sequence is one of increasing acidity, and consists of basalt at the base, overlain successively by feldspathic basalt characterized by large phenocrysts of feldspar, andesite, dacite, and rhyolite. All members of this series are not necessarily present in any one locality, but their succession when present is invariable as stated.

The paper also establishes the occurrence in northern Quebec of two important sedimentary series, both apparently of pre-Huronian age. One of these, the Nemenjish series, has been found by the writer in one locality only. It consists of a series of garnetiferous gneisses, mainly the recrystallized form of impure sandstones, which still exhibit bedding and other characteristics of sediments. The rocks rest with structural conformity on the surface of the ancient lavas, and some evidence is given to show that they probably are to be correlated with the Grenville series. The other sedimentary series, the Mattagami, has been found in five different areas. Evidence based on the character of the sediments in each area, the sequence of the formations in each series, the structures, and the relations to older and younger rocks, is cited to show that they are all of one age. The evidence relating to their position in the geologic column is less satisfactory, but they appear to overlie the Nemenjish series with unconformity, and to be much older than the Lower Huronian, or Bruce series.

In addition to these matters of principal interest, the paper discusses a number of theoretical considerations. One of these may particularly be mentioned. The explorations of northern Quebec show the existence of a fairly sharp boundary line, on one side of which limestone is a member of the Grenville series, while on the other side it does not appear. The significance of this line is discussed, and the conclusion reached that it represents an ancient topographic break, either a shore line or the boundary of a submerged plateau.

THE THURMAN-WILSON FAULT THROUGH SOUTHWESTERN IOWA, AND ITS BEARINGS[1]

JOHN L. TILTON
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WHY THE EXTENSION OF THE FAULT HAS BEEN OVERLOOKED

It may seem remarkable that an important fault should extend from near the southwest corner of Iowa to the central part of the state, with indications that it may actually extend to the "Driftless Area," and very little evidence of the presence of such a fracture exist in the literature of the state.[2] There are, however, reasons for this lack of previous recognition. The strata of the Missouri stage of the Pennsylvanian, in and beneath which nearly all of the displacement in southwestern Iowa took place, is concealed over

[1] Published with the approval of the director of the Iowa Geological Survey.

[2] The following important references may be noted:

J. E. Todd, "On the Folding of the Carboniferous Strata in Southwestern Iowa," *Proceedings of the Iowa Academy of Science*, I, Part I (1889), 61; "Some Varied Conclusions in Iowa Geology," *ibid.*, XIII (1906), 184.

G. L. Smith, "Carboniferous Section of Southwestern Iowa," *Iowa Geol. Surv.*, XIX (1909), 612.

C. R. Keyes, "Controlling Fault Systems of Iowa," *Proc. of the Iowa Acad. of Sci.*, XXIII (1916), 103; "Extent and Age of the Cap-au-Gres Fault," *ibid.*, XXIV (1917), 61.

Keyes's 1916 article was published during the summer, a year later than the field work by which the present writer discovered that near Stennett the Thurman-Wilson fault of Todd and Smith did not become an anticline but continued as a fault. In Keyes's two papers he is chiefly concerned with the Fort Dodge and the Cap-au-Gres faults, but in spacing the faults in his first paper he represents the "Red Oak fault" (the term he uses for Todd and Smith's fault between Thurman and Wilson quarries) as extending far to the northeast without giving any reason for opposing Smith's view that the fault became an anticline near Stennett, and calls the throw four hundred feet instead of three hundred feet, as reported by Smith. He also continues this fault line west to Hebron, Nebraska, without stating his reason for disagreeing with the geologists of Nebraska. However, it should be noted that near Bloomington in Franklin County, about seventy-three miles west of Hebron, Professor Erwin H. Barbour mentions and illustrates "one major and several minor faults of one to four feet displacement" (*Nebraska Geol. Surv.*, IV, Part VII, Pl. 12).

much of the area by a thick deposit of Dakota sandstone; and the entire area is deeply covered with drift, through which almost no outcrops of underlying strata appear. Especially is this true of the Missouri stage in the northern half of the area, the area north of the fault plane. Further, the Missouri stage in southwestern Iowa is represented by fourteen different sets of limestone beds separated by intervening beds of shale. The limestones themselves have shaly partings of various thicknesses, and the shaly members have limestone beds. Through all these beds there are the same species of fossils and the same general assemblage of forms, so that at present, at least, the worker who uses the fossils must associate the assemblage and relative abundance of fossils with the sequence of the beds. In this way a few lines of evidence can be made out that have an important bearing. Detailed work later on the fossil content and the relation of each bed will doubtless yield valuable returns.

South of the fault plane the varying dip of the strata accords in places with the slope of the stream beds; and no information had appeared in that area that revealed what beds became thinner beneath the drift.

THE FAULT

The writer finds that the Thurman-Wilson fault of 300 feet near the Missouri river in Fremont County does not become an anticline[1] toward Stennett, but that it is a normal dip or slightly oblique fault, extending between Fox quarries in the extreme southern part of Cass County and Briscoe (three miles further east), with upthrow on the north side, with displacement of 284.5 feet, and with fault plane dipping steeply to the southeast. This line of fracture continues northeast across Adair County, either in a slightly curved line or in a parallel fault or faults (Fig. 1). The southeast part of Guthrie County is the limit toward the northeast to which the writer has thus far traced the evidence of faulting in the field.

At the few places where a measurement of dip was obtainable a marked irregularity of dip was found that in general was at right angles to the strike of the fault plane, and thus at right angles to

[1] G. L. Smith, "Carboniferous Section of Southwestern Iowa," *Iowa Geol. Surv.*, XIX (1909), 636.

the general dip of the strata in that quarter of the state. North of the fault the upthrow side has been removed by erosion till no esacrpment has been left, while on the downthrow side the lesser amount of erosion has left strata far to the east, with offset of thirty-five and a half miles. North of the fault plane the strata beneath Lewis, Cass County, are seventy feet thinner than recorded in the log of the deep well at Clarinda, Iowa; and south of the fault

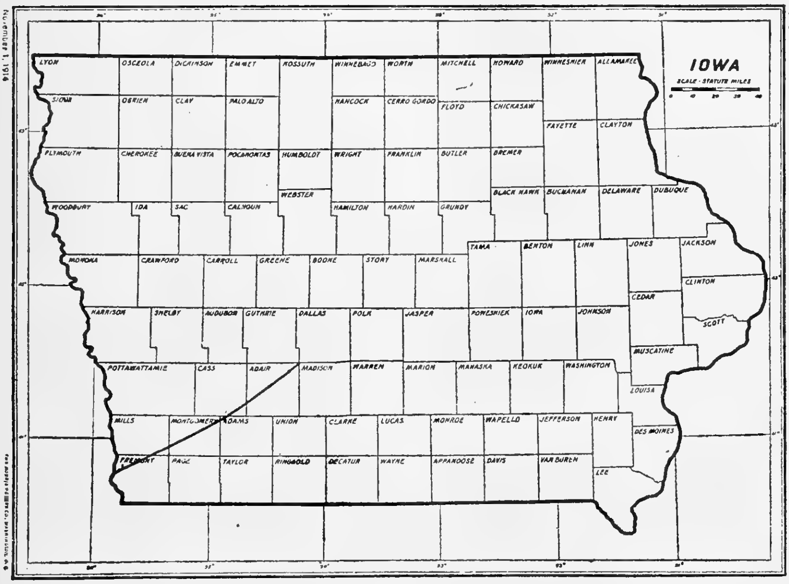

FIG. 1

plane they diminish in thickness 235 feet further within a distance of 41 miles from Briscoe, Adams County, to the "Backbone" west of Winterset, in Madison County. The most marked thinning is immediately beneath the Oread limestone, where in Missouri Hinds and Greene report a faunal break.[1] This is to be noted in contrasting a section northeast-southwest north of the fault plane with a parallel section south of the fault plane. The section from Reno to Briscoe across the fault plane connects these two sections (Fig. 2).

[1] Hinds and Greene, "Stratigraphy of the Pennsylvanian Series," *Missouri Bureau of Geology and Mines*, XIII (2d series, 1915), 155.

In order to express the relation of the beds that outcrop along Middle River in the eastern part of Adair County it has seemed desirable to represent the base of the Deer Creek substage as it meets the bed of Middle River, which in a straight line is ten and three-fourths miles northwest of the base of the Oread substage where it outcrops in Harrison township. As the strata rise to the north this makes it appear as if the Tecumsey shale became thicker to the northeast, when in reality all of the strata become thinner in that direction. In both these diagrams the dip is magnified eighty-eight and a third times.

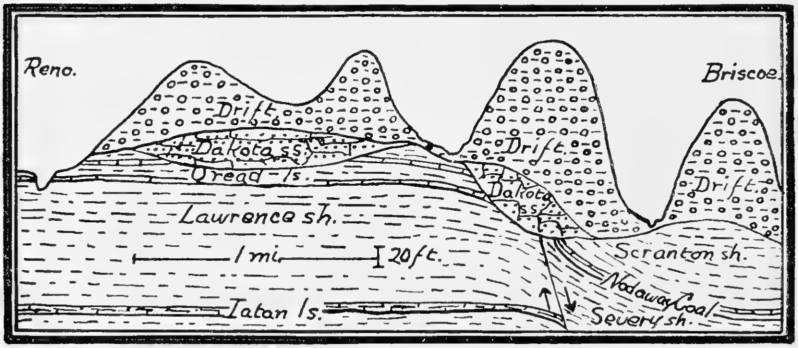

Fig. 2

The effect of this faulting on the location of outcrops is expressed in the block diagrams representing the changes that have taken place. It should be particularly noted that the limestone (Oread) which, on the north side of the fault plane, appears at Lewis and at the Fox quarries in the southwest part of Cass County, appears, on the south side of the fault plane, close to Middle River as it leaves Adair County, and also extends into the southwestern part of Madison County (Figs. 3 and 4).

IMPORTANT BEARINGS

Coal.—For the first time we now recognize why Nodaway coal found in the southern part of southwestern Iowa is not also found in the northern part of southwestern Iowa, except in a small area close to Thurman, Fremont County. Prior to this it was supposed

that the fault at Thurman changed into an anticline near Stennett, in which case there ought to be Nodaway coal north of the anticline. The recognition of the fault should prove of considerable economic value in preventing expenditure for prospecting for the Nodaway coal seam north of the fault.

The presence of the fault with uplift of 284 feet north of this fault plane is a new factor of importance bearing on the question

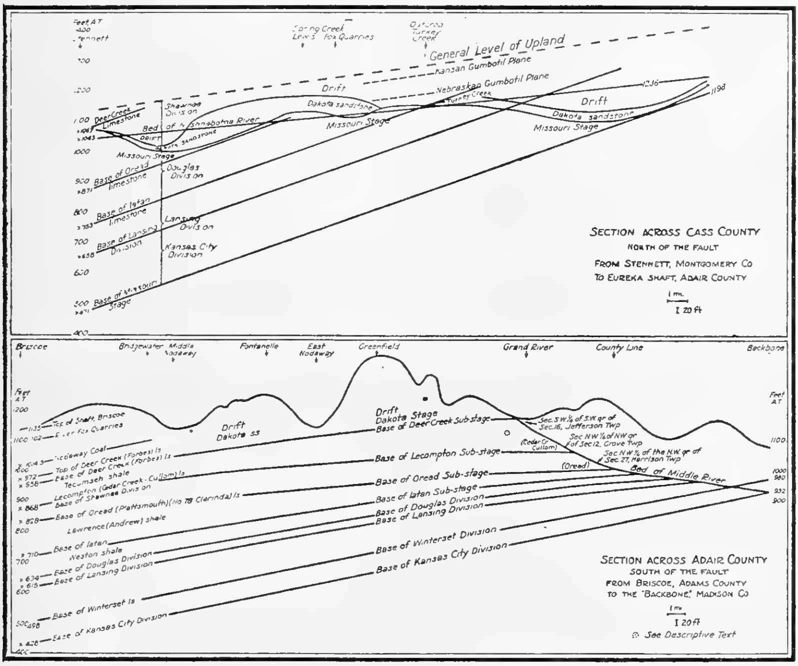

FIG. 3

of the depth of the Des Moines stage (the chief coal-bearing beds) farther north in the west central part of the state, even though the determination of the position of such beds is complicated by warping of the strata (if not by other faulting), by the great unconformity beneath them, and by the pre-Cretaceous erosion of their surface. The presence of thick beds of Dakota sandstone above the Des Moines stage and of thick deposits of drift above the

Dakota sandstone, apparently preclude the possibility of successful mines even if coal were located.

The presence of this fault and of others in a parallel direction with uplift to the north has also an important bearing with reference to the distribution of coal toward the north and northeast that is very noticeable in northern Adair and southern Guthrie and Dallas counties,[1] and, combined with erosion, explains the westward trend of exposures of the Des Moines stage in this region. It also introduces a new factor to combine with unconformity at the base of the Des Moines stage to explain why coal is found in certain localities (as near Panora and Boone) and not in others.

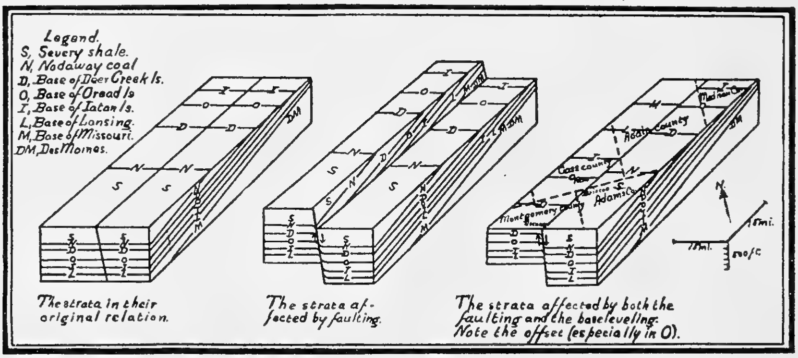

FIG. 4

Oil.—The presence of a dip fault extending through southwestern Iowa toward the oil fields farther southwest, with strata in Iowa monoclinal, dipping southwest, and crossed by low anticlines,[2] present a series of facts that cannot be overlooked with reference to oil, even though no traces of oil have been found. Across the river in Nebraska a little fault exists in Jones Point

[1] In view of the presence of this parallel fault Bain's report on Guthrie County makes very interesting reading (*Iowa Geol. Surv.*, Vol. VII). On pp. 428–29 he describes the upper division of the Des Moines stage as duplicating the lower division, and on p. 455 states that beds found "probably represent the upper portion of the Cherokee shales." Leonard (VIII, 91) speaks of an anticline in the southwestern part of Dallas County, the county next east of Guthrie County.

[2] George L. Smith, "Carboniferous Section of Southwestern Iowa," *Iowa Geol. Surv.*, XIX, 624.

that Todd[1] and Smith[2] thought a continuation of the Thurman-Wilson fault in Iowa. It seems strange that there should be a displacement of 300 feet on the Iowa side of the river and of but a few feet on the Nebraska side, and even more strange now that we know that the fault continues to the northeast with but little diminution of displacement to at least near the center of Iowa. Perhaps there is a displacement further north or south in Nebraska that has not yet been located.

Why no oil has been found in southwestern Iowa, southeastern Nebraska, and northeastern Kansas has received no satisfactory explanation as yet in published reports. With the consent of G. E. Condra, professor of geography and conservation at the University of Nebraska, I call attention to his oral statement that in the southeastern part of Nebraska granite was found at a depth of five hundred feet from the surface and penetrated for a depth of a thousand feet. This great mass of granite lies between southwestern Iowa and the oil fields further southwest, and, whatever other conditions are involved, bars underground circulation through formations that farther southwest are oil-bearing.

Border of the Missouri stage.—North of the fault plane (the upthrow side) erosion has given the east-west trend of the Missouri stage in Guthrie County. South of the fault plane (the downthrow side) the base of the Missouri stage extends far to the east. The extension to the eastward is thus not simply an uneroded mass of a highland region, as formerly supposed, but an uneroded portion left protected on the downthrow side[3] of a fault plane. Still further to the northeast, even to the "Driftless Area," along the general direction of the Thurman-Wilson fault may be noted east-west extensions of the various formations as mapped, as if the effect

[1] J. E. Todd, "On the Folding of the Carboniferous Strata in Southwestern Iowa," *Proc. of the Iowa Acad. of Sci.*, I, Part I (1889), 61; also XIII (1906), 184.

[2] G. L. Smith, "Carboniferous Section of Southwestern Iowa," *Iowa Geol. Surv.*, XIX (1909), 612.

[3] No one has as yet determined whether or not a continuation of Keyes's Cap-au-Gres fault bounds the eastern side of the Missouri stage in Iowa. He describes the fault as extending from Leon, Iowa, southeast to Vincennes, Indiana, but he gives no data with reference to the Iowa end of the line ("Extent and Age of the Cap-au-Gres Fault," *Proc. of the Iowa Acad. of Sci.*, XXIV [1917], 61).

of the disturbance were a factor in determining surface distribution well across the state. Investigation has not, however, by the writer been extended in the field to this part of the state.

AGE OF THE FAULT

Since the Dakota sandstone lies on both sides of the fault plane and rests on the truncated surface of various strata of the Missouri stage with no evidence of a fault scarp detected beneath the Dakota sandstone, it appears that the faulting began in the interval between the deposition of the Missouri stage and the deposition of the Dakota stage, that the fault scarp was well removed before the subsidence that accompanied the deposition of the Dakota sandstone, and that any additional faulting has not been very pronounced since that time. That there has been some later movement is possible, since at Crystal Lake shale included between the sandstone strata is found to dip in the general direction of the dip of the limestone (Missouri). If there was any movement along the fault plane any escarpment that formed at the surface of the sandstone has since been removed by erosion.

Variations in dip of the sandstone that correspond to variations in dip of the limestone along the fault plane have not been detected. It therefore appears from this argument also that about all faulting with accompanying disturbance[1] was completed before the Dakota sandstone was laid down. In this interval of time there was in the interior and eastern United States one marked period of disturbance, the Permian. In distant regions (Appalachian and Ouachita) the faulting was of the reversed type. Here it is of the normal type. The reversed faulting of the Permian may have been accompanied or followed by relaxational movements in the same or the next period. To this interval of time (Permian-Triassic) it at present seems necessary to refer the major part of the faulting, and perhaps all of it.

[1] From a study of the joint planes it also appears that the jointing in the Missouri stage is related to the faulting and to the uplift toward the northeast (Permian-Triassic), while the jointing in the sandstone is related to the uplift toward the northwest (post-Cretaceous), though affected by the presence of the fault plane and the joint planes, and also affecting those planes.

REVIEWS

The Geology of South Australia. By WALTER HOWCHIN. Pp. xvi +543. Figs. 330 and geological map. Adelaide: Government Printer, 1918.

Hitherto there has been no book which treated geologic processes and the general principles of geology from the Australian standpoint, although *The Geology of New South Wales* by Süssmilch may be cited as an admirable text on the historical geology of that interesting state. A feeling that there was need for a work on general geology with illustrations drawn from Australia has led to the present volume.

This volume is in two divisions. The first portion, which makes up more than half of the book, deals with geologic processes, the materials of the earth, and dynamic principles; the second portion outlines the historical geology of South Australia. While limited space precludes an exhaustive treatment of geologic principles, the reader nevertheless finds a great deal of well-illustrated material within these pages. The examples, illustrations, and concrete facts, taken largely from the Australian continent, come with a special freshness to the geologist of the Northern Hemisphere, to whom they are largely new and decidedly welcome.

A few points of dissent may be noted. The author's classification of the different forms of glacial deposits is perhaps not altogether orthodox from the viewpoint of others, as may be illustrated by the following statement, which appears under the heading of "Unstratified Glacial Deposits," on pages 146–47: "Subglacial streams wear irregular channels through the ground moraines, and when the ice disappears irregular ridges or mounds of drift are scattered over the valley bottom and are known as eskers, in Iceland; kames, in Scotland; osars, in Sweden; and drumlins, in America." On page 215, below a diagram illustrating slaty cleavage in a much-folded section, the statement is made that "cleavage planes preserve an exact parallelism and identical strike over wide areas, and are independent of the foldings of the rock as well as the bedding planes." Instead of being independent of the folding, flow cleavage has recently been shown to be developed parallel

to the axial planes of the folds, and to afford one of the prettiest keys to the interpretation of the larger units of structure in areas of complexly deformed rocks.

The second half of the volume, upon geologic history, brings out the fact that fewer geological systems are represented in South Australia than in any other Australian state, for the reason that a few systems cover a great extent of the country to the exclusion of the others. No Silurian, Devonian, or Triassic beds have been recognized, and Eocene beds have not as yet been definitely determined.

Among the most important systems are the Cambrian and the Permo-Carboniferous, in which occurred the very remarkable glaciations for which South Australia has become famous. The Cretaceous beds which surface a very considerable portion of South Australia form what is believed to be the greatest artesian basin in the world, yielding an abundant supply of usable water that is of the greatest economic importance in the development of some of the driest parts of Australia. These advantages, however, are shared with New South Wales, Queensland, and the Northern Territory. Following the discussion of each period in South Australia is a brief description of that system in the other Australian states.

The illustrations are good, and the book should prove useful to the working geologist outside of Australia as well as to the Australian student.

R. T. C.

VOLUME XXVII NUMBER 6

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

EDITED BY

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With the Active Collaboration of

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ROLLIN T. CHAMBERLIN, Dynamic Geology

SEPTEMBER-OCTOBER 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, London and Edinburgh
THE MARUZEN-KABUSHIKI-KAISHA, Tokyo, Osaka, Kyoto, Fukuoka, Sendai
THE MISSION BOOK COMPANY, Shanghai

September-October 1919 Vol. XXVII, No. 6

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

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Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

Among articles to appear in the early numbers of *The Journal of Geology* are the following:

The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin. By W. H. Twenhofel and F. T. Thwaits.

A Laboratory Field Study of Cobble Abrasion. Preliminary Report. By C. K. Wentworth.

Compilation and Composition of Bituminous Coals. By Reinhardt Thiessen.

The West Point Salt Dome, Freestone County, Texas. By E. DeGolyer.

Classification of Springs. By Kirk Bryan.

VOLUME XXVII NUMBER 6

THE

JOURNAL OF GEOLOGY

SEPTEMBER-OCTOBER 1919

CRYSTALLIZATION-DIFFERENTIATION IN IGNEOUS MAGMAS

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INTRODUCTION

A formal definition of the term magma is seldom given in petrologic literature, but it is plain from most writings that the word is intended to signify completely molten rock. Etymologically magma is perhaps more definitely applicable to a liquid with much suspended solid matter, that is, to a sort of mush. In this sense the term might designate igneous material in which crystallization was well advanced, and, while such usage should perhaps not now be urged, it is none the less true that magma in this latter sense is of fundamental significance in the genesis of igneous rock types. In his paper discussing the crystallization of magmas[1] in which that process was advocated as the fundamental factor in differentiation, the writer pointed out the special importance of two stages, the early stage of crystallization, when crystal settling may occur, and the late stage of crystallization, when squeezing out of residual liquid may occur. Throughout most of the discussion of crystallization-differentiation, however, particular attention was

[1] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement.

given only to crystal settling. Since the publication of that paper a number of writers have pointed out various features of igneous rocks for which crystallization-differentiation has seemed to them to offer no adequate explanation. These objections have arisen largely from a failure to appreciate the importance to differentiation of the period when igneous material is largely crystalline, that is, the period when it is magma in that sense of the term to which attention is called above.

In the present paper the writer wishes to offer suggestions regarding some of the more general objections that have been raised against the theory of crystallization-differentiation and especially to apply it to certain phenomena for whose explanation it has been considered inadequate.

RELATIVE IMPORTANCE OF SYNTEXIS

In a recent paper on the "Genesis of the Alkaline Rocks" Daly discusses many features of the genesis of igneous rocks in general[1] and takes the opportunity of criticizing certain aspects of the theory of crystallization-differentiation. In his introduction and at other points in the discussion Daly makes statements that convey the impression that that theory, as a whole, must stand or fall with its ability to explain the alkaline rocks. A brief examination of the basis on which the theory rests will show, however, that such statements are hardly justified. From the results of a series of experiments that dealt with the crystallization of silicate melts the writer was led to the opinion that igneous rock types as we know them in the field could be developed as a result of the fractional crystallization of basic magma under appropriate conditions. The actual experimental work was carried on with mixtures of simpler constitution than the usual igneous rock, but frequently a fairly close approach to the composition of an igneous rock in its more essential aspects was accomplished. In such instances the conclusions drawn from the experimental work may be considered to be of correspondingly greater reliability. If we examine the experimental data we find that such close approach was made only in the case of the subalkaline rocks, and in the development of the

[1] *Jour. Geol.*, XXVI (1918), 97–134.

theory of petrogenesis it was only after these data had been applied to the problems of the subalkaline rocks that a possible solution of the alkaline rocks became apparent. In short, then, the conclusions arrived at in the case of the subalkaline rocks represent but a short extrapolation from the experimental data, whereas in the case of the alkaline rocks the extrapolation is a long one and correspondingly subject to error. While there is no reason at present for receding from the position taken regarding the genesis of alkaline types, it is quite possible that the position might prove wholly untenable without any necessary doubt being cast on the strength of the hypothesis that the subalkaline rocks, at least, are derived by processes of differentiation in which fractional crystallization is the primary control.

The writer's hypothesis, then, refers the diversity of igneous rocks to the differentiation of basic magma through a spontaneous power resident within the magma and resulting from its own crystallization. Daly's hypothesis likewise assumes original igneous material of a basic nature, but considers that it has little power of spontaneous differentiation and that it acquires a significant tendency to differentiate only when equilibrium is upset by the assimilation of foreign material. For each great family of igneous rocks a particular type of foreign material has been assumed to be the special agent. To Daly assimilation is all-important, to the writer it is a mere adventitious circumstance. There is nothing, however, in the writer's hypothesis that justifies Daly's statement that he assumes differentiation to affect only purely juvenile magma without foreign contamination.[1] Daly makes this statement in his discussion of the writer's definition of differentiation, in which discussion he directs his attention more toward the form than toward the substance. In another part of his paper (pp. 88 and 89) the writer describes his conception of the *differentiation of a magma that has suffered foreign contamination.* The interpretation that Daly puts upon the definition, while perhaps not an impossible one in the light of its wording, is rather surprising in anyone who has read the whole paper as carefully as Daly has evidently done. The phrase "without foreign contamination"

[1] *Jour. Geol.*, XXVI (1918), 117.

was inserted in the definition to make it expressive of the general agreement among petrologists to exclude from the category of differentiation those variations of igneous rocks that result purely and solely from assimilation of foreign material. That syntectic magma so formed could not suffer differentiation was no part of the intent of the definition.

In that part of the paper in which he discusses the differentiation of a syntectic magma the writer does, however, state his belief that such differentiation must usually be of limited scope, giving his reasons and describing the limiting factors. Contrasted with this is the assertion of Loewinson-Lessing, to which Daly offers adherence, that "a small degree of contamination with foreign material may change equilibrium in the magma, which, therefore, separates into strongly contrasted parts."[1] Such a generalized statement leaves one wondering as to the nature of the equilibrium referred to. Between what is the equilibrium? What is the nature of the strongly contrasted parts? Are they solid, liquid, or gaseous? Do rocks show the evidences of such processes? Have analogous processes been encountered in experimental science, and is the analogy of real significance?

In going on to a discussion of differentiation Daly proceeds to enumerate what may be called the units of differentiation. Some of these are presumably the strongly contrasted parts formed as a result of the disturbance of equilibrium mentioned above, but no particular mention is made of those that are to be so regarded, nor is any discussion offered of the manner in which solution of solid rock causes the separation of the units.

The units enumerated by Daly are the following:

1. Contrasted fluid phases of an initially heterogeneous magma, including parts particularly rich in volatile constituents.[2]

2. Solid crystals (fractional crystallization).

3. Mother-liquor left after partial crystallization.

[1] This is Daly's form of expression of the Loewinson-Lessing idea.

[2] Units of type 1 need not be considered, for according to Daly's own statements on the page immediately preceding, "rock phases resulting from originally different parts of the magma can be called differentiates only by destroying the useful definition of differentiation already adopted by most petrologists," and in this the writer concurs.

4. Non-consolute liquid fractions (liquid immiscibility).

5. Material of fused country rock, not diffused into the original magma (ultra-metamorphism in part).

6. Original magma locally charged with material dissolved from the country rock but slowly diffusing from the source of supply (syntexis).

Units 5 and 6 are plainly produced by the acquisition of foreign material but cannot be regarded as a separation of the original magma into contrasted parts as a result of this acquisition. The contrast is rather between the original magma and the included foreign material. No doubt such units are real factors in differentiation, but one may reasonably question whether they are of great importance. Differentiates formed from such material would have no necessary consanguinity with other differentiates formed from the magma itself, since their composition would depend principally on the nature of the included material, that is, on a purely accidental circumstance. It is, however, the fact that differentiates do normally show consanguinity that has led to the whole conception of differentiation in petrology. A differentiate formed by the accumulation of these clots of foreign material would necessarily show a very simple chemical relationship with the available foreign material. It is the fact that this simple relation does not exist that led Daly himself to reject purely marginal assimilation, and that should furnish an equally cogent reason for rejecting accumulation of xenolith material as an important factor.

Daly's case is much stronger in this respect when he assumes complete assimilation (usually abyssal) of the foreign material and subsequent differentiation of the syntectic magma, for then all the differentiates would show the requisite consanguinity. We are thus brought back to a consideration of the separation of phases (in the more definite physicochemical sense of the term) as the fundamental factor in differentiation, and the possible units then become those enumerated by Daly as 2, 3, and 4. The processes involved, namely the separation of a crystalline phase or of a non-consolute liquid phase, must be regarded as possible factors in the differentiation not merely of Daly's syntectic

magmas but of normal uncontaminated magmas. Daly considers differentiation as particularly prone to occur in syntectic magma because "equilibrium is upset" by the foreign material. The writer, on the other hand, gives his reasons for believing that the chilling effect normally consequent upon the immersion and solution of foreign material in a magma is sufficient to limit very materially the differentiation of magma that has been so affected,[1] and thus arrives at substantial agreement in this respect with Harker when he makes the statement, "Hybrid rocks are barren." In this connection it seems desirable to consider a statement made by Shand, to which Daly refers with approval.[2] The statement is that foyaitic or phonolitic magmas may enter "into chemical combination with the silica of invaded rock masses. *The reactions thereby induced would be exothermic and would tend to raise the temperature of the magma. The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution.*"[3] In short, one might say that the addition of solid rock to a magma is, in this case and possibly in others, a mere adding of fuel to the flames. The conception probably had its origin in the long-used terms "acid" and "basic" as applied to igneous rocks, and in an unconscious extension of the analogy implied in these terms. It is true that when an acid is added to a base they unite with avidity, so much so that one must make the addition with care on account of the consequent rise in temperature. No such care is necessary when silica is added to molten nephelite.[4] Even at a temperature of 1550° C., where the product of the reaction (albite) is superheated over 400° C., silica dissolves in nephelite with excessive reluctance. Indeed experimental study suggests that the following general equation could be written with some confidence: molten rock + solid rock = molten rock $-x$ cal. It is not improbable, however, that, in some cases at least, the following equation would hold: molten rock + molten rock = molten rock $+x$ cal. In other words,

[1] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 85–86.

[2] *Jour. Geol.*, XXVI (1918), 110.

[3] Italics are mine.

[4] N. L. Bowen, "The Composition of Nephelite," *Amer. Jour. Sci.*, XXXIII (1912), 50.

it may be regarded as not improbable that two molten magmas might in some cases mix with evolution of heat, but that the solution of solid rock in molten magma is ever accompanied by evolution of heat may be regarded with extreme doubt. It is this reasoned conviction that has led the writer to limit the importance of assimilation.

LIQUID IMMISCIBILITY AS A FACTOR IN DIFFERENTIATION

Having in mind then the factors that may be considered to restrict the formation and differentiation of syntectic magmas, we may now return to the question of the separation of phases as the agency of differentiation of magmas, presumably dominantly juvenile and uncontaminated. The possible phases are, as we have seen, the units 2, 3, and 4 of Daly. Units 2 and 3 are, of course, necessarily concomitant, and to them the writer assigns the fundamental rôle in differentiation, but Daly is inclined to belittle their importance in favor of unit 4, that is, non-consolute liquid phases. The writer considers these to be non-existent in silicate magmas, this conclusion being based in part on experimental evidence. Not a single example of liquid immiscibility among silicates has been encountered in experimental work, in metallurgical practice, or in any of the many industries where molten silicates are treated. The single example of immiscibility of which there is good evidence in natural rocks, that between silicates and sulphides, is promptly revealed experimentally and in metallurgical practice. To many, however, the experimental evidence will never be convincing. When the range of experimentation with silicates shall have been extended to pressures of 20,000 atmospheres it will be possible to state that at pressures of 30,000 atmospheres wholly different phenomena might occur. Or again, an experiment made by human hands will probably never be prolonged to such a degree that its duration might be measured in centuries, so that it will always be possible to say that the time factor was not adequately considered. However, it is desirable to give some consideration to that experimental evidence which Daly brings forward, and which seems to him to indicate the probability of immiscibility under high

pressures. The suggestion is that high pressure may induce undercooling, and that immiscibility may result from the undercooling. This suggestion arose from experiments made by Bridgman, in which undercooling of liquids became more marked under higher pressures. Daly imagines that magmas may become similarly undercooled under pressure, and that in the undercooled condition unmixing may occur. Assuming the undercooling, it must be admitted that a certain possibility of the formation of non-consolute liquids is thereby introduced, for examples are known in which mixed liquids that are otherwise completely miscible develop immiscibility when undercooled. But such liquids reveal this peculiarity by having a freezing-point curve of a peculiar and characteristic shape.[1] Curves of this shape, or even remotely suggesting it, have not been noted among the liquidus curves for silicates, so that it may be regarded as unlikely that undercooling can develop immiscibility in silicates.

Quite apart, however, from the question of the probable effect of undercooling, we may point to the complete failure of igneous rocks to show evidence of undercooling when occurring in the largest masses available for human inspection, viz., batholiths. Indeed, if we consider the series that begins with a glassy lava, passes through a glassy lava with spherulites, through felsitic and fine granular textures, and ends with a coarse granular panidiomorphic texture, we find definite evidence of a continuous decrease in the degree of undercooling under which crystallization took place. The abyssal rocks are therefore characterized by a decidedly limited degree of undercooling, and the great magma reservoirs (if by this is meant something deeper than batholithic masses that become exposed) are exceedingly unlikely seats of significant undercooling. All of this is in accord with the laboratory experience that if one wishes to undercool a substance he must use a small quantity of it. The particular conditions not covered experimentally and urged by Daly as possible conditions favoring immiscibility do not, therefore, seem promising in that direction.

The writer's second reason for rejecting immiscibility is not adequately stated by Daly. He states it as being the "high

[1] Boeke, *Grundlagen der physikalisch-chemischen-Petrographie*, p. 113.

melting temperatures of olivine, magnetite, and other components of monomineralic rocks." This is in reality a collateral consideration, the reason being rather that natural rocks fail to show the kind of evidence that they would of necessity show were immiscibility a fact; indeed, it is incredible that anyone who has followed the process to its inevitable consequences could favor immiscibility in magmas.

A feature of igneous rocks that has led Grout,[1] Daly, and a number of others to favor immiscibility is the fact that two adjacent rocks that are evidently closely related frequently show a very abrupt transition from the one to the other. Yet a brief consideration of liquid immiscibility should show that it is not as likely to give discontinuous variation as is crystallization. It is true that if two liquids that are only partially miscible are shaken together in a flask two different liquids are formed, and if the flask be set aside they will become two separate layers with a definite bounding surface. If the temperature is kept constant these two distinct and sharply bounded layers will persist. However, if the immiscibility is the result of cooling a homogeneous solution the behavior is not so simple. In this case a certain amount of immiscible globules should form in the liquid when a certain temperature is reached, and, even if time were allowed then for the collection of the globules as a separate layer, more immiscible globules would form *in each layer* as soon as cooling was resumed. And when cooling had proceeded to the point where crystallization ensued a marked increase in the separation of immiscible globules would occur in association with, and as a necessary consequence of, the separation of crystals. We thus see that immiscibility is not a process taking place at an early stage of cooling as a result of which a sudden separation of a liquid into two liquid layers occurs. The separation is rather a formation of small globules that grow slowly by diffusion and can collect as a separate layer only by comparatively slow movement in response to gravity. Neither is immiscibility a process that is completed at a very early stage in the cooling history, and of which all evidence is destroyed. It is a process that may begin very early but must continue until the

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), 656.

later stages of crystallization, and the evidence of it would be as obvious and unfailing as the evidence of crystallization itself. The complete collection of *all* the immiscible liquid as a separate and distinct layer is as unlikely as the complete collection of a kind of crystals whose separation continues until a late stage.

We may perhaps make clear these facts regarding immiscibility by discussing the simplest possible binary example. Figure 1 presents the temperature-composition relations. When a liquid of composition x is cooled to the temperature FK, liquid of composition K, that is, a liquid rich in B, begins to separate from it, and as cooling proceeds the composition of the one liquid changes along FE and of the other along KD. The liquid represented by points on FE decreases in amount, and that represented by points on KD increases in amount. The first separation of liquid must be represented by the formation of minute nuclei that grow to larger and larger globules as the cooling proceeds, and as a result of the slow diffusion of material to these globules. There is no reason why this process should be accomplished any more rapidly for separated liquid than for separated crystals. If the separated globules were heavier than the general mass of liquid they would sink, and here enters the possibility of the growth of these globules to much larger dimensions than crystals, because two globules encountering each other may coalesce. The formation of very large

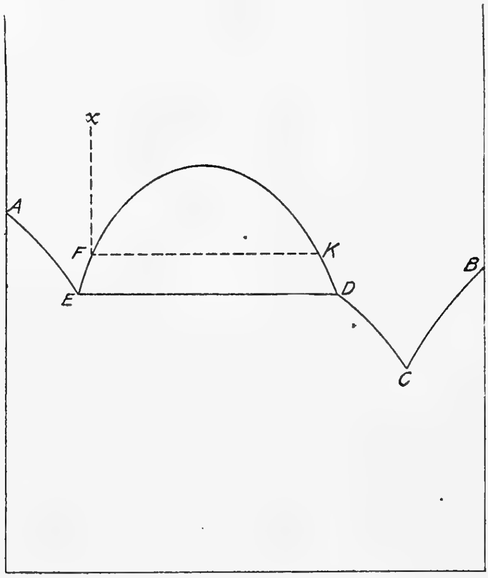

FIG. 1.—Illustrating behavior of a binary mixture with partial miscibility.

globules in this manner would result in their more rapid accumulation as a separate layer. It should be noted, however, that this rapidity of accumulation could never result in the complete accumulation of all the globules as a separate layer. If, for example, cooling were interrupted at some temperature between *FK* and *ED*, and time allowed for the accumulation of all the globules as a separate layer, as soon as cooling was resumed new globules would form in each layer, and their accumulation by the slow process of gravitative adjustment would begin again. It is plain then that whatever complications are assumed the magma must arrive at the temperature *ED* in a blotchy condition, many of the blotches being of rather large dimensions as a result of the coalescence of globules. By large dimensions is meant a diameter several times, perhaps very many times, the diameter of the crystals in the average plutonic rock. At the temperature *ED*, when the liquids in equilibrium have the composition *E* and *D*, crystallization begins, crystals of *A* separating. It is important to note the nature of the first crystals separating, for it will be recalled that the liquid separating was rich in *B*. Those who advocate the separation of olivine, pyroxene, plagioclase, etc., as immiscible liquid tacitly assume a correspondence between the kind of material that would separate early as a liquid and the kind of material that we know from experimental and petrographic experience separates early as crystals. As a matter of fact there is no necessary relation, and the fact that correspondence must be assumed in each individual case is sufficient in itself to throw doubt on a process requiring such an assumption.

Continuing the consideration of the cooling of the mixture, which had been carried to the stage of the beginning of crystallization, at the temperature *ED*, we find that crystals of *A* would separate, and that as a necessary consequence more liquid of composition *D* would be formed and some liquid of composition *E* would be used up. These reactions would continue at constant temperature with the amount of crystals *A* and the amount of liquid *D* increasing at the expense of liquid *E* until finally all of liquid *E* would disappear, when the whole mass would be made up of about 80 per cent of crystals *A* and 20 per cent of liquid *D*. We thus see that up to a time when the mass is largely crystalline two liquids are

present, and the crystalline product cannot fail to show the blotchy condition that this predicates. The evidence of immiscibility would not be confined to rapidly chilled flow and dike rocks alone, though it would presumably be especially clear in them. Further cooling would result simply in the separation of more crystals of *A* with a consequent change in the composition of the liquid from *D* to *C*, where eutectic crystallization of both *A* and *B* would occur. It will be noted too that the liquid *C*, which is the *last* material to crystallize, is closely related in composition to the liquids *K-D*, the *first* material to separate as a liquid. This is important in connection with the well-recognized parallelism between "Differentiationsfolge" and "Kristallizationsfolge." If liquid immiscibility were a prominent factor, or even a subsidiary factor, in the differentiation of igneous rocks no such parallelism would exist.

If we return now to those discontinuous changes of composition in associated igneous rocks that have led to the suggestion of immiscibility, we may make the discussion more concrete by referring to a specific case for which immiscibility has been invoked, viz., the case of the Duluth laccolith. Grout has concluded that the material of this great laccolith or lopolith, as it has been called, was intruded as a homogeneous magma, that crystallization-differentiation controlled by convection currents and gravity ensued, whereby the peridotite and banded gabbro were produced, and that when a certain stage of crystallization had been reached the material of the red rock separated from the gabbro as an immiscible liquid.[1] The first stages of this process, with modifications that are perhaps not fundamental, the writer is able to agree with, but he can see nothing in the described Duluth rocks to warrant the assumption of immiscibility, nor indeed in any other igneous series that shows this association of gabbro and granophyre without intermediate types. The kind of immiscibility assumed by Grout, namely that which ensues only after a certain amount of crystallization has occured, is in no sense different from that which we have discussed. Indeed some of the liquids of the system described show this behavior, viz., those having a composition lying between *A* and *E* (Fig. 1). This liquid, which formed only after crystallization

[1] *Jour. Geol.*, XXVI (1918), 658.

was well advanced, would form throughout the gabbro, and some of it would have to rise through several thousand feet. Granting that this was possible at a certain stage and complete accumulation of the liquid took place, what has become then of the further quantity of like liquid that must have separated when the conditions causing its first separation became intensified, that is, when crystallization of the gabbro was carried farther? Unquestionably clots of such material should occur everywhere throughout the gabbro. When it is realized too that experimental studies have shown beyond peradventure that a material rich in alkalic feldspar and free silica is a possible crystallization residuum of a gabbro magma and especially of an olivine gabbro the assumption of immiscibility is seen to be quite gratuitous. This is more especially true for that great number of examples where the acid material occurs in part as granophyric interstices in the gabbro phase, for there it is plainly a crystallization residuum occupying crystallization interstices and not occurring as the clots that one would expect of an immiscible liquid.

CRYSTALLIZATION AS THE CAUSE OF DISCONTINUOUS VARIATION

This association of gabbro and granophyre without intermediate types, of which Grout has collected a number of examples from the literature, is a feature of igneous rocks well recognized by the writer.[1] It is true that in discussing crystallization-differentiation it was shown that a complete series might be formed, extending from gabbro to granite with every intermediate step, but there is no necessity that the series be complete. Only in a very large mass is such a series to be expected, where not only the great size but conditions of comparative quiet concurred to produce great freedom in the settling of crystals. In masses of moderate size the differentiation, if it can be so called, may be a localized affair occurring about each individual crystal, where the separation of the earliest crystalline material from its mother-liquor is accomplished not by its sinking but by the formation of zones about it. In this case the late differentiate occurs merely as interstitial material. If this zoning action is combined with only a limited amount of sinking of

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 227.

crystals one can obtain a mass showing the last liquid as an upper layer and also as interstitial material in part of the rest of the mass. This is likely to give a pair of rocks showing that marked contrast between a granophyre on the one hand and a diabase or gabbro with only granophyric interstices on the other. Daly has failed to grasp the significance of zoning in producing granophyric interstices and seeks to destroy the whole theory of crystallization-differentiation at one fell blow by pointing out that pyroxene, olivine, and plagioclase have not sunk out of granophyric diabase.[1] It is not necessary that they should, for the prevention of reaction between crystals and the liquid from which they separated may be accomplished, as we have seen, not only by a spatial separation but also by a localized mechanical separation due to zoning.

There is, however, a third method of separation of liquid from crystals that is probably the principal agent of production of those discontinuous variations frequently seen in rock series and particularly that shown in the gabbro-granite (granophyre, etc.) association. It is the squeezing out of residual liquor at a stage when the mass is largely crystalline, and it is many times more promising as a possible cause of discontinuous variations than is any process of limited liquid miscibility, which, as we have seen, is a continuous process requiring the slow action of gravity as an ally and not significantly more competent than crystal settling to produce discontinuity. This squeezing out of liquid is a process that is at first thought difficult to visualize, yet it is one that must be a very real factor in igneous rock genesis. It is the sort of thing one may see at any time when walking on the wet sand of a beach. The foot leaves a slight imprint in the sand that is surrounded by an area where the surface of the sand is particularly wet. The mass as a whole is sensibly incapable of flow, so that the pressure of the foot results merely in a more efficient close-packing of the sand grains coming immediately under its influence, with a consequent squeezing of water into the surrounding sand, where some of it exudes upon the surface. On the other hand, in very wet sand or in mud the whole mass may flow under the foot. The filter-press action

[1] *Jour. Geol.*, XXVI (1918), 121.

exhibited by the sand is but roughly analogous to the phenomena possible in a partly crystallized magma but may serve as a starting-point in the discussion. The relative movement of liquid with respect to crystals by this general method is probably not normally possible with rock materials before the crystals have grown together into a mesh. In order to discuss the action here suggested we shall assume specific cases and consider, as well as may be, the mechanics of the process.

Laccolith with upper late differentiate.—Assume that a sheetlike mass of magma is injected between two members of a sedimentary series, with slight arching of the upper member so that a flat laccolithic mass is produced. The fact that the sheet was injected at that horizon may be regarded as being probably determined by the competency of the member immediately above it. If this terrane is being acted upon by a compressive thrust the tendency will be to shorten the lateral dimensions, and the competent member will yield by forming a more pronounced arch, while the relatively incompetent beds immediately beneath the mass will yield by shortening and thickening. This action, going on slowly, will result in a thickening and shortening of the laccolithic mass, which offers no resistance until crystallization has proceeded to such an extent that the crystals touch each other and have grown together into a strong framework. When sufficiently strong this crystal mesh may finally be able to sustain the thrust and cause a pause in the shortening action. The condition then existing might be represented by Fig. 2*a*. The stress may accumulate until finally the crystal mesh begins to break down, whereupon the beds beneath will yield as before, and the competent beds above will bend as before. Likewise, coincident with the beginning of the breakdown of the crystal mesh the interstitial liquid will feel the pressure of the thrust and will transmit it hydrostatically to all parts of the mass, and the vertical

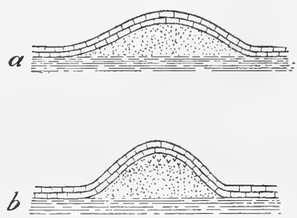

FIG. 2.—(*a*) Laccolith at an advanced stage of crystallization; (*b*) same after being subjected to lateral pressure at this stage. Shows squeezing of residual liquid (late differentiate) into the crown of the arch.

component of this hydrostatic pressure on the liquid will aid in emphasizing the up-arching of the beds of the roof. As the crystal mesh *progressively* breaks down, and the horizontal dimensions are shortened in consequence of closer packing of crystals, there will be a flow of the interstitial liquid into the space developed by the up-arching of the roof. All three actions—shortening of the lateral dimensions by closer packing of crystals, up-arching of the roof, and movement of the liquid—go on *pari passu* and are thoroughly interdependent. When the crystals have become sufficiently closely packed to withstand the thrust the whole action must cease, and of course may cease sooner for other reasons. The resultant mass is therefore, in the simplified case we have assumed, a laccolith showing marked differentiation, with a rock represented by crystalline material separated from the original magma as a lower differentiate, and as an upper differentiate material represented by a late residual liquid (Fig. 2*b*). The differentiation would be markedly discontinuous, the later differentiate would have an intrusive relation to the earlier in places, in other places there would be a rather abrupt transition, and yet the relations would not indicate successive intrusion in the ordinary sense of the term. In so far as this action is incapable of occurring before a certain degree of crystallinity has been attained, there should be a tendency toward a fairly constant contrast between the two differentiates in the matter of composition. On the other hand there is no necessity for constant relative proportions in their amounts. Associated igneous rocks when formed by this method should present, therefore, a fairly constant hiatus as compared with the complete igneous series that is capable of production under other circumstances. Any mass, not necessarily of the simple shape we have assumed but capable of being acted upon in the same general manner, should give a closely related result, so that the general phenomenon might well be of widespread occurrence. The gabbro-granophyre association fulfils every requirement.

An example of the extreme simplicity we have pictured will of course never be found. One of the principal complications results from the fact that the freezing of such a mass will take place from the outer layers inward, except for such modification of this behavior

as is introduced by crystal settling. As a result of this more advanced consolidation of outer layers an upper layer may become more or less definitely a part of the upper competent member of the stratified series and may act in conjunction with it during the process of up-arching. The later differentiate would not normally, therefore, be the uppermost. It would, indeed, be located more nearly toward the central part of the mass according to the degree of this freezing inward from the roof.

Sheet with thin central late differentiate.—In certain cases where the freezing has been nearly symmetrical at the top and bottom of a sheetlike mass a horizontal thrust, occurring at a time when there was still a thin layer mostly liquid centrally placed, might cause a general shortening of the lateral dimensions of the sheet, with consequent thickening vertically. These would take place concomitantly and would be accomplished by closer packing of the crystals in the outer layers, where crystallization was well advanced, and a thickening of the originally thin central liquid layer by inflow of the interstitial liquid from the outer layers. There would thus be formed a mass having a thin central later differentiate with an intrusive to transitional relation to its surroundings, and with a distinct tendency toward a streaky development, for the liquid squeezed in from the layers where crystallization was well advanced would differ from the liquid already present in the narrow central band when this action began.

Thick central late differentiate.—There is also a very simple method whereby a sheetlike mass, whether dyke or sill, can develop locally a very thick, centrally placed layer of this late differentiate. It is the warping of the containing walls of the sheet, with consequent thickening of the sheet in a certain place and thinning of it elsewhere. If this takes place at any time except at a late stage of crystallization it will normally have no significant result in the way of differentiation. If it takes place at a time when the crystal mesh has considerable strength it may have important consequences. We shall consider a segment of the sheet including a part that has been thickened. Figure 3*a* represents part of the original sheet and Fig. 3*b* the same after warping of the walls. In the section where the sheet is thinned the crystal mesh will be broken down and

the crystals more closely packed. There is an intermediate neutral zone in which the sheet retains its original width and the crystal mesh remains undisturbed. This portion therefore acts as a permeable partition through which the interstitial liquid of the thinned portion passes.[1] As the walls begin to move apart in the thickened portion the crystal mesh will part along a median plane, for there it is weakest, and the interstitial liquid from the thinned portion will flow in to occupy the space afforded. At no time will there be any space in the sense of empty space. The movement of liquid into the space will be absolutely concurrent with, and perhaps a contributing cause of, the development of the space. The action will continue until a proper balance of the forces involved is reached. In certain sections the thickness of the sheet may be increased to several times its original value, and the late differentiate may be a very thick central band, indeed several times as thick as the narrow bands of the early differentiate on either wall. The thinned portions will normally be thinned only a moderate amount, so that relatively large areas must be thinned. The late differentiate would again have an intrusive relation to the earlier material on the walls, with, however, "welded" contacts and locally a transitional relation of a more or less abrupt nature. This action could take place only at a late stage of crystallization, when the crystal mesh had very considerable strength, if only for the reason that the neutral zone must have sufficient strength to withstand a considerable difference of hydrostatic pressure on opposite sides of it, for there would be very great frictional resistance to the flow of liquid.

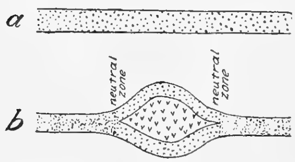

FIG. 3.—Sections of a tabular mass, dyke, or sill: (a) at an advanced stage of crystallization; (b) after warping of walls at this stage and squeezing of residual liquid (late differentiate) into expanded section.

[1] For the purpose of presentation of the conception in particularly simple form this definite neutral zone is assumed. Its existence is, however, not essential to the action described. It is merely necessary that the breakdown of the crystal mesh should go on progressively as stated on p. 408. This will bring it about that the portion not yet broken down acts at any instant as a permeable partition preventing the passage of crystals and permitting the passage of liquid from the portion breaking down at that instant.

It is suggested that the various kinds of filter-press action that have been discussed hitherto probably cannot take place before the mass is 80 per cent crystalline. In all cases we should have a marked hiatus in the crystallization series that could have formed under conditions favoring continuous differentiation, that is, conditions favoring crystal settling. Even with the slow cooling and the quiet cooling requisite for crystal settling a certain amount of the filter-press action we have discussed may occur when crystal accumulation has proceeded to the appropriate degree.[1] No general discussion of the combined effect will be attempted. Instead an explanation will be offered for the phenomena exhibited by the special example, the Duluth lopolith.

DIFFERENTIATION IN THE DULUTH LOPOLITH

On this igneous mass Grout has recently published an interesting series of papers. It is a large, sheetlike body mainly of gabbroid composition but showing differentiation, with masses of peridotite at the bottom, a great thickness of olivine gabbro with striking banded effects and anorthositic facies, and at or near the top a so-called "red rock" or granophyre. Grout thinks that crystallization was a prominent factor in the production of differentiation, and that convection was the dominant agent in bringing about the observed distribution of crystals. There was also a wholly different type of differentiation, according to Grout, which involved the separation of the red-rock magma from the partly crystallized gabbro magma as an immiscible liquid. To this latter phase of his conclusions certain objections have already been offered that later will be referred to again. Any type of differentiation in which crystallization is the fundamental factor is, in the writer's opinion, much more likely to occur, and any promising process that may be put forward as conducive to the localized accumulation of crystals is unlikely to meet with opposition from the writer. Convection does not, however, seem to offer any promise. Grout introduces a type of convection called two-phase convection, in which a mass of liquid containing suspended crystals is considered

[1] A combination of the two actions is probably the most promising explanation of many monomineralic masses.

to act as a unit and to sink in virtue of its greater aggregate density. It was evidently suggested by Daly's two-phase convection, in which the two phases involved were liquid and gas that gave a low aggregate density. It is known that masses of foam possess some of the attributes of a rigid body, and it might therefore be expected that localized highly vesicular masses of lava might act as a gravitative unit, but nothing is known to warrant the extension of the idea to a liquid containing suspended crystals. Moreover there appears to be no necessity for appealing to this unlikely process, since ordinary thermal convection would be equally effective and can hardly fail of occurrence in a cooling mass of magma.[1] However this may be, we may now proceed to consider the supposed effects of convection. Grout makes some calculations on the rate of convection which indicate that crystals formed at the cooling portion near the top could be carried to the bottom in half an hour. No reason is offered for this precipitate haste. Undoubtedly many years were available; indeed Daly considers the time available to be embarrassingly long and offers it as an objection to crystal settling that the results are often very meager when the duration of crystallization is considered. Moreover, it should be realized that a current that could carry crystals down in half an hour could carry them up again in half an hour, particularly a current in which a mass of liquid with suspended crystals is supposed to act as a unit. The lagging behind and lodgment of the crystals at the bottom as the currents sweep over the floor, which Grout considers would occur, would undoubtedly be a factor in the case of ordinary thermal convection at any rate (its possibility in the two-phase convection pictured by Grout may be doubted). It should be realized, however, that this occurs in spite of convection and in virtue of the superior density of the crystals rather than in virtue of convection, and the really important question is whether crystals would accumulate at the bottom more effectively by this dragging-behind process than they would by simple settling. In other words, does convection act as an aid or as a deterrent to

[1] It should be noted that the writer has never doubted the reality of convection in magmas. He merely doubts its efficacy in producing differentiation.

crystal settling? The answer suggested by experience is that it would act as a deterrent. Sedimentation in nature is always delayed by convection, and in the laboratory when one wishes to make separations by means of heavy solutions one always obtains a more ready separation by jacketing the heavy solution in order to prevent even the very moderate convection that results from the slight draughts in the laboratory.

Perhaps, however, the more important reason for advancing convection was not its greater efficiency in bringing about accumulation of crystals as compared with the "far-fetched" process of settling of crystals. Possibly the particular reason was the banding of the gabbro. In order to explain the banding it is necessary, however, to assume a simplicity of convection that experience of that phenomenon does not warrant. It is known, for example, that a mass of liquid experiencing convection may divide up into columnar cells of hexagonal section, each of which has its own system of convection characterized principally by vertical currents. While it need not be urged that convection in a large mass of magma would be exactly of this nature, it seems inevitable that a very large number of currents would be set up whose motion would be principally vertical, and that any banding of the rock that might result from convection would be principally vertical. There seems little reason to believe in a great current sweeping over the floor and depositing its load in bands parallel to the floor in the manner Pirsson[1] and Grout have suggested. However, assuming that such a current did exist, it is noteworthy that in order to explain banding it is necessary to make the further assumption of a rhythm in crystallization, such that the crystals brought down by convection vary in their nature as time goes on and may even alternate. And convection is supposed to have a remarkable advantage over crystal settling in producing alternation of layers as a result of this rhythmic crystallization. But while I do not urge rhythmic crystallization I would point out that the crystals brought to the bottom by settling would show precisely the same alternation as those brought there by convection if this rhythmic crystallization can be assumed.

[1] *The Igneous Rocks of Highwood Mountains*, U.S. Geol. Survey, Bulletin 237.

When we come to a consideration of the more intimate details of crystallization we find this same tendency to urge an advantage of convection over settling, an advantage that has no real existence. In the case of the bodies of magnetite, for example, it is pointed out that the best concentrations are centrally placed in the gabbro and not at the bottom, and to explain this it is pointed out that magnetite is, "at least partly, later in time of crystallization" and "would remain liquid until the lower parts of the chamber were filled with rock." Is the explanation not equally applicable to the process of crystal settling? Is there anything in that process that demands the settling of a crystal before it exists? It is true that the writer referred to the accumulations of iron ore as evidence of settling of crystals because they have been described by others as occurring at the base of the Duluth mass, and it is safe to say that in many cases some of the iron ore crystallizes very early, but the writer has always been opposed to the unrestricted acceptance of the notion that all the ore minerals separate early.[1]

We come now to that very special feature of the near-uniformity in the nature of the plagioclase in all parts of the gabbroid portion of the mass, a feature that has been considered to favor especially the idea of convection. Vigorous convection would of course keep plagioclase crystals suspended and in a slowly cooled mass would permit perfect adjustment of their composition to that of the surrounding liquid, so that there would be no necessity of the appearance in the final product of any very basic plagioclase, bytownite, or anorthite. But the rôle assigned to convection by Grout is not so much that of keeping crystals suspended as that of aiding in their accumulation in layers by dragging along the bottom, and, at a time when the rhythm of crystallization was in a phase such that the crystallization of plagioclase dominated, the layer formed is supposed to show a corresponding dominance of plagioclase. These plagioclases, dragging behind and caught in the viscous border, have according to Grout "there slowly, maintaining equilibrium, adjusted their composition to that of the surrounding magma." It should be realized, however, that in so far as basic

[1] N. L. Bowen, "The Order of Crystallization in Igneous Rocks," *Jour. Geol.*, XX (1912), 457.

plagioclases accumulate at a certain place in excess of the amount that could have separated from the liquid at that place, the liquid there surrounding them is incapable of completely making them over into the average plagioclase of the mass.[1] It makes no difference how the excess of plagioclase arrived at that place, the laws of physical chemistry will not be suspended in favor of those arriving by the convection route. The fact that those portions of the mass that are particularly rich in plagioclase do not have significantly more basic plagioclase than other parts may therefore be regarded as a very serious objection to accumulation of plagioclase by convection and indeed to any process involving the accumulation of plagioclase by a positive active motion on its part relative to the liquid from which it separates.

The theory of crystal settling, however, does not demand any positive action of plagioclase, at any rate not until a quite late stage of crystallization. Just as settling is not regarded as possible for a crystal that does not yet exist, so it is not regarded as possible for a crystal unless it is heavier than the liquid. Grout is able to refer to a place (p. 33) where I have discussed the effect of the sinking of plagioclase, but reference to that page will show that there simple mixtures of albite and anorthite are being discussed. Manifestly basic plagioclase crystals will sink in a liquid having the composition of more acid plagioclase, but if femic material is dissolved in the liquid the problem is not so simple, and on another page of the same paper (p. 79)[2] reference is made to this fact. There the following statement is made: "It appears, indeed, that plagioclase crystals may at the earlier stages of crystallization be only very slightly heavier than the liquid at most and possibly even somewhat lighter." In another paper this suggestion is elaborated and the behavior of plagioclase is discussed at some length.[3] It is pointed out that plagioclase "remains practically suspended in the liquid with probably a very slight tendency to rise at first and the whole of the liquid is available for the production of the change of composition that ensues as the temperature falls. Thus, though

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 212.

[2] These page numbers refer to those in "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement.

[3] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 211.

the earlier crystals of plagioclase are basic bytownite, they are, in nearly all cases, gradually made over into labradorite by the liquid in which they remain suspended." The statements could hardly be more specific, and Grout's reference (with its accompanying objections) to my statement regarding a simple mixture of anorthite and albite is hardly to the point when such definite consideration of the actual case of gabbroid magma has been offered. We have seen then that the specific objections to crystal settling that Grout offers are in part due to a misconception of that process, and that in many cases where he supposes a convective action to have advantages over settling the advantage has no real existence as far as explanation of the phenomena of the Duluth gabbro is concerned. However, it must be conceded that Grout's main contention is substantially correct, viz., that the theory of crystal settling in the simple and generalized form in which it has been stated does not offer an adequate explanation. We have seen that his convective action is likewise inadequate. As an offset to so much destructive criticism a constructive suggestion will be ventured. The suggested explanation will involve two principal assumptions: first, that the igneous mass of the Duluth lopolith was injected as a sensibly homogeneous and completely liquid magma, and secondly, that the action which produced the basin-like form of the mass took place in part contemporaneously with the period of crystallization of the magma. The first of these conclusions is, it should be remarked, in complete accord with Grout's conclusions. Under five heads Grout points out the impossibility of belief in the intrusion of heterogeneous liquid, a process that the writer has suggested as a possible result of the squeezing of liquid from a crystallizing mass.[1] This suggestion should be applied only to cases where the evidence is strong that there were two liquids. I am wholly in accord with Grout that it is a quite inadequate explanation of the banding of the Duluth mass and indeed of most rocks showing primary banding. Usually such banding is to be referred to movement during crystallization.[2]

[1] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 27 and 83.

[2] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 236 and 237.

We shall begin then with a mass of gabbroid magma wholly liquid and already injected into its present position. When cooling had reached a certain stage crystallization began, and the earliest crystals, olivine and perhaps some titaniferous magnetite, were precipitated. As a result of currents in the liquid, whether from thermal convection or wholly mechanical causes, free settling of crystals was much hampered, so that a large proportion of the crystals remained suspended. In spite of this deterrent action, however, some of the crystals of these early minerals did accumulate on the bottom, where they formed masses of peridotite and presumably also of iron ores in some cases. In the meantime, crystallization of both pyroxene and plagioclase had begun. The plagioclase was at first a basic bytownite. It remained suspended because nearly of the same density as the liquid, and, as cooling and crystallization proceeded, it adjusted its composition to approach labradorite. The free sinking of pyroxene was hampered, presumably by currents, as was that of olivine, so that no accumulation of pyroxenite was accomplished. A certain amount of accumulation of pyroxene did occur, however, together with that of olivine, and the pyroxene crystals augmented the mass of peridotite at the base. There was also a certain part of the liquid from which both olivine and pyroxene crystals had settled out practically completely and that contained only suspended plagioclase crystals.

The mass is now entering a stage when in its lower portions, constituting say one-fifth of the total thickness, crystals are in contact with their neighbors and are beginning to grow together at corners and along edges. This action becomes important when the residual liquid and the crystals have each about one-half the volume of the total mass. In the upper portions the crystals are somewhat more widely spaced, the more so as the height above the base increases, but this feature is not so very marked, because crystal settling has been limited by the lack of quiet conditions. The bottom-most layers including peridotite may be regarded as practically entirely crystalline, with only a small proportion of residual liquid.

Origin of banding.—There is then a tendency toward a layering of the mass on a very large scale but no suggestion whatever of

the complicated banding that the finally solidified rocks show. In order to explain the production of banding it is necessary to assume that the action that produced the basin-like shape of the mass was going on continually during the period of crystallization. When the proportion of crystals was small this action could have no effect on the distribution of materials, but when the proportion of crystals began to pass the 50 per cent mark it may have had an important effect.

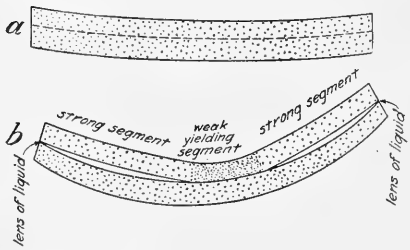

FIG. 4.—Showing the effect of warping on a crystallizing mass: (*a*) shows portion of a mass when it reaches stage at which warping begins to be effective; (*b*) shows the effect of warping causing compaction of crystals locally and the formation of lenticular pools of residual liquid. Density of stippling is intended to indicate the relative, though not absolute, degree of compaction of crystals in various parts immediately after the action. Final result is a banded rock showing that contrast in composition that existed between liquid and crystals at the time of the action.

We shall consider, for simplicity and convenience, the possible results of the bending action as applied to segments of two adjacent layers. The bending will tend to produce a shortening of the upper layer relative to the lower one, and a shortening thrust is therefore developed in the upper layer. This upper layer may reasonably be supposed to have certain portions that are relatively weak and others relatively strong that may be illustrated diagrammatically as in Fig. 4. It may be supposed too that all of the yielding to this shortening thrust will take place in the weak portions of the layers, and that the strong portions will act as practically rigid plungers. The yielding of the weak portions will likewise relieve the strong portions from any bending force, and a strong portion can therefore retain its original shape, with the consequent development of a long, narrow space between it and that part of the lower layer immediately adjacent to it. At first thought it would seem impossible that this space could develop, and if by space is meant empty space this impression would be entirely justified, for the strong segment, though capable of acting as a rigid plunger, would have no real strength as an arch. It should be noted, however,

that the strong segment and indeed the whole crystal mesh which we are considering is a thoroughly porous material permitting free passage of the liquid residual magma under its hydrostatic head. A space between the two layers could therefore develop freely, for it would fill with liquid as fast as it opened. The yielding of the weak segment, the opening of a long, narrow space between the bridgelike strong segment and the lower layer, and the filling of this space with the residual liquid would therefore go on simultaneously and indeed would be thoroughly interdependent. The yielding of the weak segment would be the result of the breaking of the relatively weak crystal mesh at the points where crystals had begun to grow together, and once instituted it would continue until the crystals were packed together rather closely with only a little residual liquid, or until the mass had acquired a strength equal to that of the segment that was acting upon it as a plunger. At this time the action would cease as far as the yielding of that particular weak segment was concerned. As a result then of this single episode two layers have been produced whose direction is practically parallel to the base of the igneous mass, one of them having a composition practically equivalent to that of the residual liquid contained in the crystal mesh at the time, and the other a composition not far from that of the crystals that had separated at the time (Fig. 4*b*). If we consider the further history of this particular part of the igneous mass as cooling and further bending proceed it will be found that the segment that had yielded will, when a certain amount of growing together of the already compacted crystals takes place, constitute a particularly strong segment and in virtue of its strength may be the means of production of a layer of the same type as itself, from a relatively weak segment sensibly along its strike, by acting as a plunger and compacting that segment. At the same time the plunger segment will produce immediately beneath itself a band of the opposite type. It is thus seen that the action, once begun, is a means of its own growth and is particularly competent to produce adjacent strongly contrasted bands. Constant repetition of this action as cooling and warping proceed should produce innumerable bands such as those seen in the Duluth mass.

If we return to a consideration of the fundamental action involved, namely the formation of a bridge as a result of the refusal of a certain layer to bend in conformance with the bending of the layer immediately beneath it, we find that this could take place only when the crystal mesh is of such a nature as to have fair compressive strength but very little tensile strength. If the tensile strength were even moderate the upper layer would be pulled into conformable shape by the lower layer, for the tension acts over a relatively large area. The crystals of the mesh must therefore be in contact but must be grown together only to a very limited degree. There is a further reason why the proportion of crystals to liquid must be limited. The bridging action can take place only when the crystal mesh is so open that pressure on the liquid is transmitted to all parts of it with great freedom and with little frictional resistance, for the bridge has no real strength to support a significant superincumbent load, and liquid must be free to flow into the space immediately below it if the potential bridge is to become a reality. On the basis of some rough experiments it is estimated that the action could take place when the mass was 50 per cent crystalline but probably not when the proportion of crystals was significantly less than that value. On the other hand, it probably could not take place when the proportion of crystals was as great as 65 per cent. The contrast between bands is therefore of a different order of magnitude from that shown in the gabbro-granophyre association. There is likewise a rather limited period for any particular portion of a mass during which this action can occur. It is believed that during this period and as a result of the action described the banding of the Duluth gabbro was produced. In this case it is possible to show the relation between the direction of banding and the forces that produced it. For many igneous masses having primary banding this relation would perhaps not be so plain, yet it would seem to be safe to state it as a general proposition that primary banding is produced by the action of warping stresses, torsional stresses, and in some cases shearing stresses, acting at the appropriate stage of crystallization.

Origin of the red rock.—Returning now to the Duluth lopolith, we find it at a stage when crystallization is fairly well advanced.

As a result of continued warping banded structure has developed in successively higher and higher horizons, broadly speaking, though as the top was approached the conditions would vary considerably, and it would seem likely that banding would not be produced as readily. However this may be, we may consider that the stage of possible development of banding has passed, and that the whole mass is approaching complete crystallinity. The lower portions pass through this stage somewhat sooner that the higher portions and finally become completely crystalline, the liquid adjusting itself continually to the composition of the crystals with which it is in contact, until finally all the liquid is used up. In upper portions some interstitial liquid still remains, and principally in those parts from which olivine has been removed by gravity the interstitial liquid becomes of a granitic nature. As the plagioclase crystals, continually adjusting their composition, approach labradorite, Ab_1An_2, the plagioclase content of the liquid approaches acid andesine, and the actual proportion of the interstitial liquid becomes rather small. This is the stage at which a lateral thrust acting on the mass may produce a squeezing upward of residual liquid and a packing together of the crystals after the manner discussed in some detail on an earlier page. It may be noted that in the upper portion of the mass the warping becomes more nearly a simple compressive thrust resulting from the tendency toward the folding in of the two horns of the crescent so that the squeezing out may be regarded simply as a result of a continuance of the warping action and as expressing its result at quite a late stage of crystallization. There is even a very definite suggestion in the shape of the lopolith as mapped of a departure from the simple crescentic form. This departure is, as might be expected, localized where the red rock is developed in force and is of the nature of a bulging of the roof (Fig. 5). Add to this the fact that the plagioclase of the red rock is on the average precisely the proper plagioclase for a liquid in equilibrium with the general plagioclase crystals of the gabbro, and it becomes rather obvious that one is, to say the least, hasty who dismisses crystallization-differentiation as a possible explanation of the gabbro, red-rock association. The red rock has, on the contrary, all the earmarks of a crystallization residuum that could have been

squeezed upward by lateral compression of part of the gabbro mass. Grout, in offering objections to crystallization-differentiation as an explanation of the red rock and in discussing in that connection the composition of the liquid, states that "before it reaches the composition of such a granophyre as the red rock of Duluth a large amount of feldspar must have crystallized from a magma too acid to yield basic labradorite."[1] On another page, however, he describes the red rock as amounting to "less than 300 feet of acid andesine." Now the liquid that is in equilibrium with Ab_1An_2 crystals is precisely of the composition of acid andesine, to be more

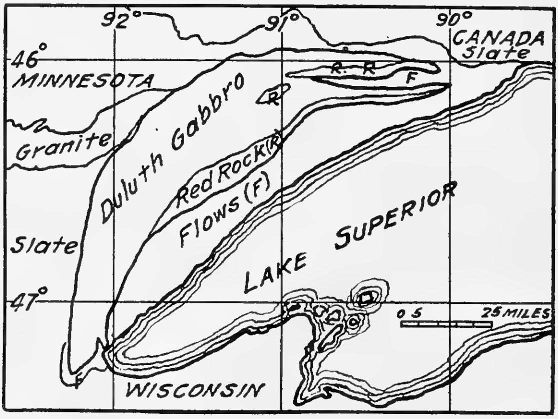

FIG. 5.—Outline map of Duluth gabbro (after Grout)

specific Ab_3An_1, so that Grout's objections fall when examined in the light of his own detailed descriptions. If the red rock represented an immiscible liquid it is rather remarkable that at the time at which it had separated it should have a composition appropriate for this final plagioclase composition.

In connection with this particular association, namely that of granophyre and gabbro, a rather definite suggestion as to conditions of possible immiscibility has been offered. It has been suggested that on account of immiscibility between water and silicates the magma separates into two liquids, the one water-rich and the other

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), 645.

silicate-rich.[1] Apart from the objections that have been raised against immiscibility in general, principally with reference to the lack of evidence of the intermediate steps of the process, a further objection should be pointed out that is applicable to this particular type. The contrast between the two liquids should be of this nature, that the one liquid should be mainly a silicate melt with a little water in dilute solution, and that the other liquid should be mainly water with a little silicate in dilute solution. Now, while it is well recognized that the granophyre of the association to which we have reference is characterized by having a greater amount of water than the gabbro, no one would go the length of claiming that the granophyre magma was mainly water with a little silicate in solution. While having, on first thought, some degree of probability the action contemplated does not appear to represent the actual phenomenon.

THE ORIGIN OF NODULES, SCHLIERS, AND RELATED PHENOMENA

Immiscibility has been invoked as an explanation of other phenomena of igneous rocks, principally the formation of monomineralic nodules and of large rock masses of a monomineralic nature. For immiscibility of this nature not even the first-thought probability can be conceded. Substances freely miscible above a certain temperature do not become absolutely immiscible on cooling, with consequent separation of pure end components as liquids. The liquids separating would of necessity be polycomponent solutions, possibly quite strongly contrasted, but nevertheless polycomponent. The liquids must likewise be solutions capable of separate existence at the temperature concerned, and in emphasis of this temperature aspect of the problem it has elsewhere been pointed out that pure molten olivine, for example, can hardly be credited at temperatures near the crystallizing range of olivine basalt. It has been suggested that the liquid need not be pure olivine but could be olivine with volatile components in solution.[2] The obtaining of such a liquid is, however, sensibly the same problem as the obtaining of molten olivine. Any liquid that separated

[1] Evans, "Congrès Geologique International," *Compte-Rendu* (XXII*e* Session, Canada, 1913), p. 248.

[2] Daly, *Jour. Geol.*, XXVI (1918), 123.

should be polycomponent with respect to its silicate content alone. A volatile component enters the system merely as a component that would distribute itself between the two separating liquids in accordance with a definite partition coefficient which is the ratio of its solubility in the two liquids. Even if we strain a point and assume that one of the liquids could be monomineralic it is necessary to imagine that volatile components distribute themselves between the two liquids in such a way that the monomineralic liquid gets many times as much as the polycomponent liquid in order that the former may remain molten at the temperature concerned. In other words, it is necessary to assume that volatile components are many times more soluble in liquid olivine, say, than in liquid basalt. Apart from the unlikelihood of such a relation the real weakness of the whole case becomes apparent when, in order to explain monomineralic masses of pyroxene, it becomes necessary to assume that volatile components are many times more soluble in liquid pyroxene than in liquid basalt, and in order to explain an anorthositic facies it is necessary to assume correspondingly greater solubility of volatile material in molten plagioclase than in molten basalt. Finally, if it is insisted that this chain of successively dependent phenomena, each fundamentally unlikely, to say the least, may nevertheless represent the facts of the case we may still turn to monomineralic rocks themselves and see if they give evidence of *excessive richness* in volatile components or so-called mineralizers. It was with this reasoning in mind that the anorthosites were examined and found to give no evidence of the presence of mineralizers *in excessive amounts*.[1] Scrutiny of the other monomineralic rocks will, it is believed, yield a like result. The marked serpentinization of peridotites is probably sometimes effected by waters of atmospheric origin (not by weathering), and where accomplished by magmatic solutions there is little reason for believing that these solutions belonged to a peridotite liquid rather than to adjacent igneous masses frequently congeneric with the peridotite.[2]

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 231.

[2] Benson, *Amer. Jour. Sci.*, XLVI (1918), 710.

It has been considered that the nodules consisting mainly of a single mineral and occurring fairly frequently in basaltic rocks may represent immiscible liquid globules. Olivine nodules in basalt are perhaps the commonest examples. The term nodules is rather misleading, for they are characteristically angular and justify the conclusion of a great number of petrographers that they are fragments torn from a mass of olivine rock (Olivinfelseinschlüsse). Rosenbusch, however, always insisted that they represent intratelluric crystallization from the rock mass in which they are found. As a matter of fact it is more reasonable to suppose that both conceptions are true, and that the nodules represent fragments torn from an olivine rock that was formed from the basalt by crystallization-differentiation. It is not necessary to suppose that the olivine settled to the bottom of an intratelluric mass of basaltic magma; indeed the characteristic occurrence of the nodules in narrow dikes and small necks of basalt suggests an action that may be of considerable importance in petrogenesis. The suggested action is the formation of crystal jams, or the clogging of the channels occupied by moving magma as a result of the packing together of crystals at a constricted point, in much the same manner as log jams and ice jams are formed in rivers. Any marked constriction of a channel in which a liquid is flowing that contains suspended solids, even in very small amount, is likely to cause such clogging. The formation of a crystal jam is highly probable in a narrow dike or neck through which basaltic magma is flowing with upward of 10 per cent olivine crystals suspended. Once formed the clogging may result in the accumulation of a considerable mass of crystals, and the passing of liquid through the mass, a liquid from which olivine and only olivine is being precipitated as yet, may cause the growth of the crystals of olivine until no interstices are left. Accumulation of pressure on the magma, aided perhaps by terrestrial disturbance, may then break the barrier and carry the olivine rock along as inclusions of the nature of olivine nodules, some of which may become rounded as a result of the resorption that olivine normally suffers. While the clogging of a channel with very early crystals, such as olivine, is to be expected only in small channels, there is reason to believe that even large channels might be similarly affected

at later stages of crystallization, and in this case, while the disrupted mass would not give monomineralic inclusions, it might readily give inclusions strongly contrasted with the magma that would produce schliers and related irregularities in the rocks formed.

In the banded peridotites of Skye, Harker describes seams of nearly pure picotite and chromite. It is possible that these may have been formed by some such action as that described above. However this may be, the petrologist should look askance at molten spinel and chromite. Molten corundum, molten olivine, and molten magnetite even with volatile components in solution are to be similarly regarded, and every possibility of explaining masses of such minerals as the result of crystal accumulation from complex magmas or of hydrothermal action should be exhausted before the probability of such melts is entertained, for the chemical difficulties in the way of their production are colossal. By hydrothermal action is meant introduction by dilute solutions as contrasted with introduction as a melt, even though it be a melt with volatile material dissolved.

ORIGIN OF THE ALKALINE ROCKS

Throughout the foregoing pages consideration has been given to phenomena exhibited only by the so-called subalkaline rocks. For such rocks we can speak with considerable assurance regarding the chemical effects of relative movement of crystals and liquid, because systems approaching them reasonably closely in composition have been completely investigated. Concerning the alkaline rocks we cannot speak with the same assurance, for not much more than a beginning has been made in their experimental investigation. Nevertheless some consideration will be given to the alkaline rocks, particularly to the question of the relationship between alkaline and subalkaline magmas. The writer has stated elsewhere the opinion that the most important of the alkaline magmas, foyaitic magma, is definitely related to granitic magma. The equilibrium reactions which take place in granitic magma, and of which the evidence is plain from the occurrence side by side of feldspars, mica, and quartz, furnish a clue to the origin of foyaitic magma. The principal reactions indicated are the breakdown of

polysilicate molecules into orthosilicate molecules and free silica, and they may be written empirically as follows:

$$KAlSi_3O_8 \leftrightarrows KAlSiO_4 + 2SiO_2,$$
$$NaAlSi_3O_8 \leftrightarrows NaAlSiO_4 + 2SiO_2.$$

Certain other reactions no doubt occur, such as

$$H_2O + NaAlSiO_4 \leftrightarrows HAlSiO_4 + NaOH,$$
$$H_2O + KAlSiO_4 \leftrightarrows HAlSiO_4 + KOH,$$

which are simple examples of hydrolysis. That such reactions are going forward in the liquid is attested by the fact that certain of the products are precipitated, the polysilicate molecules as feldspar, the orthosilicate molecules $KAlSiO_4$ and $HAlSiO_4$ in mica, and free silica as quartz. Evidently certain other products not precipitated are stored up in the liquid, and the principal of these is $NaAlSiO_4$, the liquid becoming highly alkaline and showing a high concentration of water and other volatile components when finally precipitation has taken place to such an extent that the liquid is a very small proportion of the total mass. The compound $NaAlSiO_4$, the distinctive molecule of foyaitic magma, can be precipitated from this liquid only if it is removed from the presence of quartz. In the presence of quartz the reaction is simply reversed, and the polysilicate feldspar is precipitated instead of the orthosilicate nephelite. It is not impossible that rapakivi structure and certain perthites whose albite lamellae appear to have been formed by reaction may represent the stage of reversal of this reaction. It is not essential that such structures be present, however, for commonly the using up of this liquid would be accomplished merely by continued growth of albite or closely related plagioclase crystals. There does appear, however, to be a particular tendency toward a precipitation of albite later than that of orthoclase (rapakivi-like though not necessarily having the particular rapakivi structure) in granites that are related to nephelite syenites. It should be noted, however, that this highly alkaline and highly aqueous liquid that is thus formed as the crystallization of granite becomes far advanced is a very fugitive material, and that the crystallization of a large mass of granite must proceed very slowly at this stage.

Throughout a long period this liquid is therefore more or less free to escape into the surrounding rocks, where it is used up in producing metasomatic reactions of various kinds. The materials of this liquid may therefore be frequently, perhaps normally, unrepresented in the igneous sequence for this very reason. Foye has brought forward quantitative evidence of the introduction of alkaline material in great quantity from granitic magma. Following Daly he imagines that these alkaline liquids have been produced by reaction between limestone and granite, but it is not at all clear how this can be considered to apply to the particular case under discussion. In its original form the limestone-syntectic hypothesis was rather simple, and, as the writer has stated elsewhere, it assumed rather likely reactions. The most important reaction was the taking of silica by the lime to form lime silicates, the free silica being used up first and later some of the silica of feldspar molecules with consequent production of feldspathoids. However, it is imagined in this particular case that limestone reacts with granitic magma but does not desilicate it, in fact leaves it still a granitic magma, and yet reacts in such a way as to produce large amounts of alkaline liquors, of which part are introduced into the invaded limestones and part crystallize with formation of nephelite syenite. The manner in which this can occur is by no means so easily followed. On the other hand, it appears to afford a natural explanation if it is supposed that biotite granite magma is normally capable of supplying this alkaline liquid, and that it is produced by reactions of which we have direct evidence in the granite itself. The liquid may be used up by introduction into surrounding rocks or by partial reversal of these reactions if it remains in the interstices of the granite. On the other hand, if it is separated from the granite in such a way as to form a distinct liquid it will give rise to a mass of nephelite syenite and may indeed further differentiate to give derivatives of nephelite syenite.

In the paper in which this mode of origin of nephelite syenite was proposed it was stated that a continuance of the process of settling of crystals could produce nephelite syenite from granite in the same manner as granite itself may be produced from gabbro. This manner of separation of the liquid from the crystals is not now considered likely, indeed the essential reactions have probably

not proceeded adequately until a late stage in the crystallization of granite, when crystal settling was no longer possible. The only method of separating the liquid at this stage is the method of the squeezing out of residual liquid by the breaking down of the crystal mesh under the action of outside forces. If this be true, alkaline magma can be produced only as a result of the action of outside forces, whereas subalkaline magmas, while they too can be so generated, may nevertheless be generated spontaneously by crystal settling. It is possible then that the alkaline rocks might show a tendency toward a definite relation to earth movements[1] not exhibited in the same degree by subalkaline rocks, but the writer is unable to see at present what the details of this connection may be.

The succession of igneous rocks deduced from the foregoing considerations—from basic through silicic to alkaline—has been discussed in some detail elsewhere.[2] An objection to this has been raised on the basis of the fact that in the Pacific basin there are basic rocks and alkaline rocks and none of the intermediate silicic rocks.[3] It should be noted, however, that these objections are based entirely on the evidence of effusive rocks and the occurrence of a magma, as an effusive mass depends on certain factors other than its generation within the crust of the earth. Daly has, for example, presented figures that show that granitic material is twenty times more abundant than basaltic as deep-seated masses, whereas basaltic material is fifty times more abundant than granitic as effusive masses. There is therefore something about granitic magma that limits very seriously its occurrence in effusive types, even though it may be abundantly present as subjacent masses. We need not go into the question of what these factors may be, though some readily suggest themselves. The significance of the fact in this connection is that the types that happen to be exposed in an effusive sequence may give but a poor indication of the genesis of their magmas, and it may be taken as a general rule that fundamental relationships are much more likely to be deducible from plutonic masses. When we turn to the evidence of plutonic masses

[1] Such as that suggested by Harker in the classification into Atlantic and Pacific types.

[2] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 55 ff.

[3] Holmes, *Science Progress*, XI (1916–17), 68.

on this question we find that they speak in no uncertain voice regarding the intimate connection of silicic with alkalic rocks.

This association of silicic and alkalic rocks, we have seen reason to believe, is of fundamental significance and is a fact very difficult of explanation on the basis of the limestone-syntectic, desilication hypothesis. Ordinary granites, nordmarkites, and highly siliceous alkaline granites are world-wide associates of nephelite syenites.

In yet another respect the limestone-syntectic hypothesis lacks support. The proponents of syntexis as a general phenomenon frequently support their claims by pointing to the fact that fragments of siliceous rocks immersed in gabbro frequently show rims of a granitic nature about them, and that fragments of quartzite immersed in nephelite syenite may show rims of alkaline granite. These and like observations at least demonstrate the possibility of certain reactions, though one may still doubt their quantitative importance in petrogenesis. In the case of the reaction between feldspar-bearing magma and limestone to produce feldspathoid-bearing magma no support of this kind is to be found. Magmas of all subalkaline types have at times included blocks of limestone that have been made over into lime-silicate rocks, yet in no case are these inclusions surrounded by rims of alkaline rock. The limestone-syntectic hypothesis lacks, therefore, even that measure of support that is afforded syntexis in other cases through the occurrence of the reaction aureoles mentioned.

SUMMARY.

In this paper some of the objections that have been raised against the theory of crystallization-differentiation are considered, and its adequacy to explain certain phenomena, for which it has been considered to fail, is pointed out. The supposed advantages of liquid immiscibility in explaining discontinuous variations are considered, and reasons are given for believing that no such advantages exist. On the basis of crystallization explanations are suggested for discontinuous variations, particularly those noted in the association gabbro-granophyre. A suggestion is made as to the origin of primary banding with particular reference to the Duluth lopolith.

THE RICHARDTON METEORITE

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At 9:48 P.M. Mountain time, June 30, 1918,[1] a meteorite was seen to fall in the country between Richardton and Mott, North Dakota. Pieces fell on both sides of the line between Stark and Hettinger counties within a strip about 9 miles wide from north to south and 5 miles wide from east to west. The center of this area lies in altitude 46°37′30″ N. and longitude 102°16′17″ W., about 20 miles south of Richardton.

The following data in regard to finders and specimens have been collected. The finds are arranged in geographical order from north to south.

Names of Finders	Section	Township	Range	Specimens	Weight	
					Pounds	Ounces
Rochus Steiner........	26	137	92	1 piece in fragments	6	12
Geo. B. Steiner........	?	137	92	1 piece	13	......
Nickolas Kuntz	27	137	92	1 piece	11	8
				1 piece	2	10
Bernard Kuntz	27	137	92	1 piece said to weigh	9	......
				1 piece	2	4
Lewis Loran..........	33	137	92	1 piece	18	5¼
				1 piece	7	0½
				1 piece	4	......
				1 piece	0	12
Frank Miller..........	12	136	93	4 fragments	7	......
Leo Kern.............	18	136	92	11 pieces (largest 3 lbs.)	9	5½
Mat Schmidt.........	18	136	92	15 pieces	7	......
Benedict Fried........	24	136	93	24 pieces (½ to 2½ lbs.)	17	......
Jacob Fried...........	26	136	93	4 pieces	1	......
Jozim Olheiser........	28	136	92	3 pieces	2	13

This lists a total of 71 pieces, weighing 123 lbs. 6 oz. It is reported, however, that at least 60 lbs. of material in addition

[1] The date was erroneously reported as July 26, 1918, in a preliminary statement in *Science*, New Series, Vol. XLIX (Jan. 24, 1919), p. 92.

to some of that listed above were purchased on the spot by Mr. T. A. Treganza.[1] It is probable that about 200 lbs. of material have been recovered from the fall, of which the Loran boloid, weighing 18 lbs. $5\frac{1}{2}$ oz., appears to be considerably the largest.

As noted in the description of Modoc,[2] the distribution of the members of a meteorite fall follows in general the order of their size, with the largest pieces farthest in the direction of flight. The Richardton meteorite fell toward the north, and all the units weighing more than three pounds apiece came from the most northerly strip, 2 miles wide, while only one small specimen, weighing 12 oz., was found there. On the other hand, although the number of pieces found in the southern end is greater than that found in the northern part of the area, nearly all the individual examples are small.

The Richardton meteorite is of the veined, spherical chondrite class (Cca) of Brezina's classification, as may be recognized from the following descriptions of those specimens which have been studied by the writer. The descriptions are arranged in order of the size of the specimens.

1. The Loran specimen, weighing 18 lbs. $5\frac{1}{2}$ oz. (8,338 gm.), may be likened in shape to an axe-head. It is a five-sided wedge, the sharp edge being 20 cm. long, and the blunt end 12 cm. by 11.2 cm. From back to edge the piece is 18 cm. long. Part of the crust has been broken from the mass, especially from the corners. In fact the corners of most large specimens are battered because the meteorite fell at a low angle to the surface of the earth, so that most of the pieces seem to have rolled or bounded after striking the ground. Few pieces penetrated the soil and none is known to have broken through the sod.

The largest Loran specimen appears to have six subparallel veins, the traces of three of which can be followed entirely around the mass, but the other three split up into branches and are less definite. All the veins branch into two or more members, and in

[1] The writer has sent three letters to Mr. Treganza, Britt, Iowa, in regard to his purchases. However, as none of these letters brought a reply, no further information about this interesting collection can be offered in this article.

[2] O. C. Farrington, *Nat. Acad. Sci.*, Mem. XIII (1915), p. 307.

some places the branches reunite, in the manner of anastomosis. Here and there within them there is a concentration of troilite and iron. The traces of the veins stand out like welts upon the unbroken surfaces (Fig. 1); otherwise the surface of the meteorite seems fairly smooth, although variegated with the characteristic shallow depressions, like thumb-prints, which are common to many stony meteorites. In addition to the subparallel veins before noted, there are at least two others roughly at right angles to them, which are less clearly marked than the series of six. It may be there are really more than two in this group. In any case, they are not prominent, and either they are discontinuous, or else the vein-filling material is wanting in places, making them inconspicuous on that account.

The crust seems to be of equal thickness on each face, apparently being a secondary fusion surface everywhere except on the side shown in Fig. 1, which appears also to have been the side protected from the rush of air after disruption of the meteorite. All the surfaces show the system of tiny cracks, like the crazing of china, which is common to stony meteorites.

On places from which the crust is broken it can be seen that the matrix of the stone is pale gray, speckled with pale brown chondrules as large as 3 mm. in diameter. The matrix is friable and easily broken, the chondrules breaking freely out of the matrix. There appears to be a good deal of troilite, but the iron does not show so clearly because it lacks the reflecting fracture faces which make the troilite apparent.

2. The Loran specimen weighing 7 lbs. $\frac{1}{2}$ oz. (3,186 gm.) is an irregular hexahedron with three pairs of subparallel sides. It may be described as an irregular rhombohedron, of which two axes are at right angles to one another, the third axis being at approximately right angles to one axis and inclined at an angle of about 80° to the other.

The crust is almost complete except for one side, which is a nearly plane fracture surface. Almost parallel to the fractured face are veins which can be traced completely around the stone. The fracture face itself follows one of the veins, so that much of the surface is vein material. This vein is cut by two short

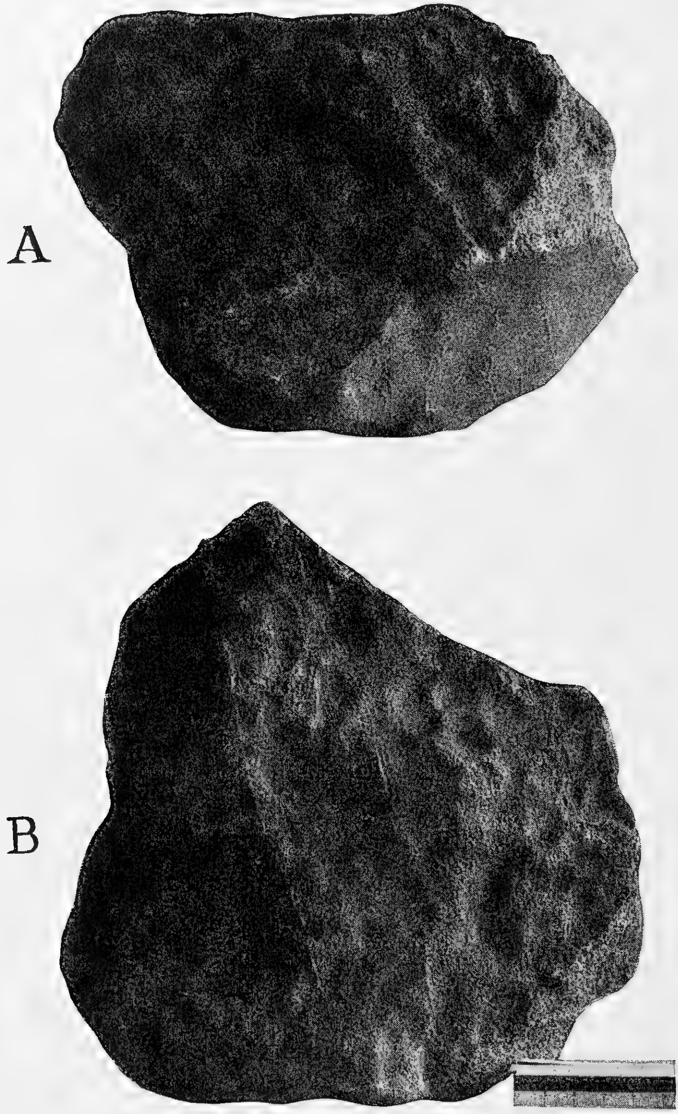


FIG. 1

A, The large, wedge-shaped specimen of the Richardton Meteorite, lying on one side, the edge of the wedge being to the left, showing traces of the veins on the smooth, primary-fusion surface.

B, Side view of the same specimen standing on the smooth face shown above, showing the secondary-fusion surfaces developed after disruption of the meteorite. The two lower corners are broken. The scale reads in centimeters.

cross-veins and offset by one. The veins in this specimen seem to be composed largely of troilite. Troilite is disseminated throughout the stone and forms ledges along the veins.

3. The largest member of Kern's collection is a well-crusted specimen, bounded by one flat side and a hemispheroid. The flat surface appears to be a fracture plane following a troilite vein. The stone weighs 1,357 gm.

4. A seven-sided boloid found by Nickolas Kuntz, weighing 2 lbs. 10 oz. (1,192 gm.), is covered with shallow depressions of the common finger-print type. It shows several veins of more than one group. There is no smooth face which may be interpreted as that sheltered during flight.

5. Preserved at the University of North Dakota is a very black coated specimen found by Bernard Kuntz, weighing 1,022 gm. One side is smooth, showing clearly the traces of intersecting veins, and the other faces are pitted with shallow depressions. Either the smooth face was the side away from the rush of air during flight, or it is of earlier origin than the rough faces, which may be secondary surfaces fused over after disruption during passage through the atmosphere.

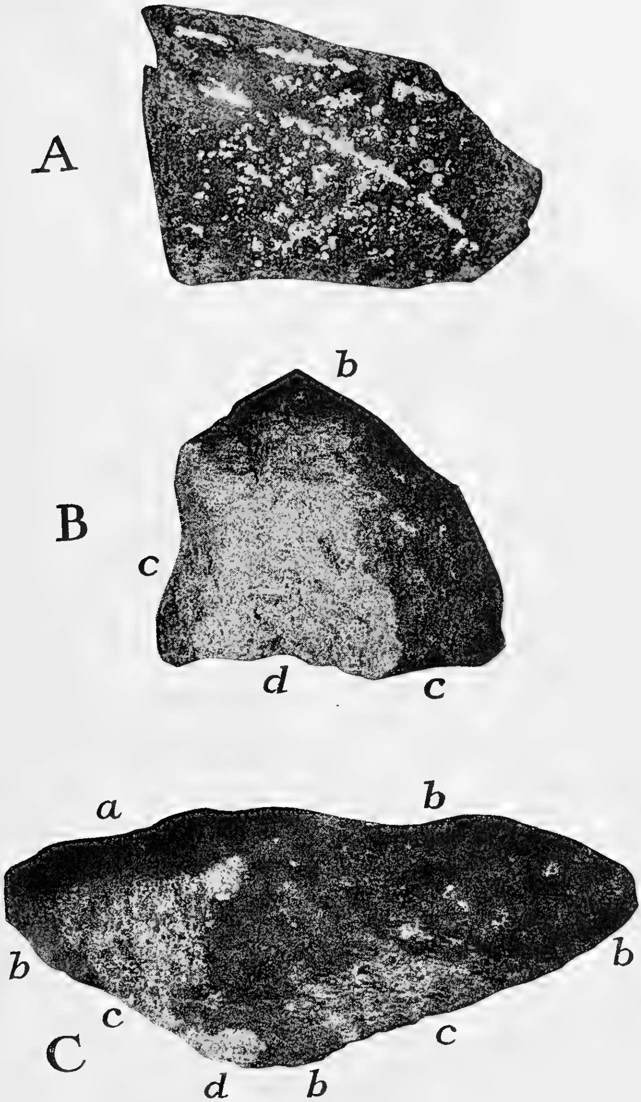
6. Fourteen small pieces weigh 515, 498, 349, 312, 309, 305, 240, 232, 207, 168, 163, 161, 127, and 123 gm. respectively. These specimens are rounded boloids covered with fused crust, angular fragments completely covered with fused crust of various degrees of denseness, pieces broken either by impact with the ground or during examination by the finders, and combinations of these groups. In many cases troilite in melted blebs embosses the fused surfaces, indicating that many secondary faces follow the planes of veins.

This group of small specimens furnishes evidence of at least three degrees of fusion. First, there are black faces which are very smooth and show the traces of veins as welts, apparently sides protected from the direct impact of air in flight. Other black faces are dappled with small finger-print-like depressions, lumps and depressions being equally covered with fusion crust, having been corroded apparently by the blast of hot air compressed in front of the meteorite during its passage through the

air. Second, there are rough surfaces, not smoothed by fusion and still bearing the roughness of original fracture, burned to a dark-brown color, the points being rounded off and black, but the depressions being unfused in places. These areas cut sharply across the black, well-fused faces, and are clearly of later origin. Third, a few small fragments have some surfaces only slightly fused; perhaps the words "scorched" or "singed" well describe the degree of fusion. Only the points of rough, broken surfaces are blackened by fusion, most of the area is light gray and unfused, but here and there outstanding pyroxene chondrules and troilite grains have melted and run a few millimeters over the unfused material. These faces, in some cases, are in the form of spalls out of the other types of fusion crust. It is clear that they are the youngest of the fused surfaces (Fig. 2, *B* and *C*).

Under the microscope it can be seen that these stones are composed chiefly of olivine, monoclinic pyroxene, glass, metallic iron, and troilite. The texture is markedly chondritic. The matrix consists chiefly of small crystals and fragments of olivine and pyroxene scattered throughout a scanty, glassy matrix. The chondrules are of the following types: (*a*) Spheroids, each composed of part of an olivine crystal. (*b*) Spheroids, each composed of part of a pyroxene crystal. (*c*) Little spheroids of colorless glass. (*d*) Larger spheroids containing well-defined olivine crystals. In some examples the crystals are crowded together, in others they are scattered in the glassy ground-mass of the chondrule. In a variety of this type the crystals appear to be arranged with their crystal axes parallel. (*e*) Glassy chondrules with radiating and fibrous cryptocrystalline texture. Some of the large pieces of olivine show many minute inclusions in irregular linear distribution.

A notable characteristic of this meteorite is the veining (Fig. 2, *A*). The veins are composed chiefly of troilite, and metallic iron and nickel. They are not continuous, for they contain areas in which there is no metallic material. The veins seem to vary in different cases from containing almost nothing but metal to carrying only troilite. In most cases metal and sulphide are mingled in a manner which suggests contemporaneous deposition or con-



Photograph by W. A. Force

FIG. 2

A, A polished surface showing the apparent concentration of metal in veins. Some of the chondrules have so high a polish that one must look closely to distinguish the metal from the polished chondrules.

B, A specimen showing the natural fracture face (*d*), the tertiary fusion surface (*c*), and a little of the secondary fusion surface (*b*).

C, A specimen showing all degrees of fusion: (*a*) indicates the primary, (*b*) indicates the secondary, (*c*) indicates the tertiary fusion faces, and (*d*) indicates the broken, unfused interior of the meteorite.

centration. Parts of the veins have been examined in both polished surfaces and in thin sections under the microscope. The metal seems to have been deposited without any violence having affected the chondrules, as a general thing; however, one chondrule seems to be represented by only half a sphere, the metal being in juxtaposition with the plane side. In most cases, nevertheless, the metal or sulphide partly surrounds or incloses the unbroken chondrules. The writer has seen no case of a chondrule penetrated by metal, although some of the chondrules include tiny grains of troilite in bordering zones. In cases where both metal and sulphide are in the vein the two are mingled in irregular shapes which have a smooth surface of contact; in some cases the troilite is scattered both within and near the borders and outside the metal, in other cases taking the place of the chief constituent of the vein and containing small irregular grains of metal.

Iron and troilite veins are not uncommon in stony meteorites. In some cases both minerals are present, and in others there is but one. Of American falls the following are reported definitely to contain iron veins: Danville,[1] Marion,[2] Farmington,[3] Estacado,[4] and Pipe Creek.[5] Troilite veins are reported in both McKinney[6] and Cosby Creek.[7] In most of these the iron and sulphide are concentrated apparently in the veins, although in most other meteorites the iron and troilite are disseminated in irregular grains throughout the mass. The relations of the minerals are commonly obscure; for example, Bath Furnace[8] has troilite intruding riven metallic particles as though of younger age than the iron, and also troilite completely enclosed in iron, indicating the opposite. But in Allegan[9] the sulphide does not occur as blebs within the iron as the silicates do, indicating that it is not necessarily either antecedent or contemporaneous with the iron. In the case

[1] Farrington, *op. cit.*, quoting Smith, p. 156.

[2] *Ibid.*, quoting Brezina, p. 296.

[3] *Ibid.*, quoting Meunier and Preston, p. 187.

[4] *Ibid.*, quoting Howard and Davison, p. 174.

[5] *Ibid.*, quoting Brezina, p. 353.

[6] *Ibid.*, quoting Brezina, p. 291.

[7] *Ibid.*, quoting Shepard, p. 138.

[8] *Ibid.*, quoting Merrill, p. 50.

[9] *Ibid.*, p. 30.

of Richardton, however, the troilite and iron seem clearly to be contemporaneous.

Polished surfaces, parallel to a vein and cutting the vein, totaling a surface of 10 sq. cm., show nickel iron containing irregular grains of troilite, in which there are three specks of metallic copper, the largest grain measuring about 0.6 by 0.08 mm. This seems to be the first report of metallic copper in a meteorite. Copper has been determined in traces by chemical analysis, but the character of its occurrence was unknown. It has been remarked before that, whatever the conditions under which metallic iron and nickel are deposited in these and similar veins in meteorites, the conditions must have been reducing in the extreme. It is not surprising, therefore, that, with iron in the reduced forms of ferrous sulphide and metal, copper also should be metallic. Copper inclosed in iron sulphide, which is also inclosed in metallic iron, may suggest that some of the sulphur was once in combination with the copper, previous to reduction of the metals.

A determination of the specific gravity of two small specimens without metallic veins, weighing 168 and 127 gm. respectively, gave the result 3.76. Specimens with veins would yield a higher specific gravity determination.

Following is an analysis by J. E. Whitfield, for privilege of early publication of which we are indebted to Dr. George P. Merrill, of the National Museum:

	Percentage
Metallic portion	19.90
Silicate portion	80.10

The metallic portion yielded as follows:

	Percentage
Fe	90.89
Ni	8.92
Co	0.15
P	0.04
	100.00

The silicate portion yielded:

	Percentage
SiO_2	44.49
TiO_2	0.10
Al_2O_3	2.46
Cr_2O_3	0.64
Fe_2O_3	4.34
P_2O_5	None
MnO	0.19
FeO	16.23
CaO	2.69
MgO	28.32
Na_2O	0.85
K_2O	0.165
	100.475

These analyses were made from fragments apparently representative of the matrix of the meteorite, but not representative of the vein material. From the absence of sulphur and copper in the analysis it appears that the vein material is generally different from the rest of the stone.

On November 9, 10, and 11, 1919, the following data and evidence were collected at the places noted.

At Mandan, 70 miles east and about 10 miles north of the locality of the fall, several people saw the meteorite. It happened that there were two troop-trains in the yards at the time and any noise the meteorite made was not noticed during the celebration.

At Dickinson, 30 miles northwest of the locality, the meteorite appeared as a bright light which went out suddenly, accompanied by a rushing, roaring sound which seemed to shake the air.

A person interviewed in Richardton was in New Leipzig, about 20 miles southeast of the locality, at the time the meteorite fell. He had just gone to bed when he was startled by a brilliant light, which he took momentarily for the headlight of a locomotive; however, he went to the window and saw a meteorite passing to the west of the town, going apparently in a northwest direction and falling at a low angle. The witness recalled that there was a roaring sound like that of an airship for about two minutes, followed by a violent explosion; it was a fearful and terrifying noise,

rattling the windows and shaking the house severely, resembling an earthquake. To others at New Leipzig it sounded like rolling artillery.

Mr. Bernard Kuntz, Section 27, Township 137, Range 92 west of the fifth principal meridian, saw the fall. To him the flight seemed to be from southwest to northeast, making the countryside as bright as day. He described the noise as like that of an airship or a motorcycle. He found several specimens.

Mr. Nickolas Kuntz lives on another quarter of the same section as Bernard Kuntz. All his family were in bed and asleep at the time, but they were awakened by the light and noise, which they took to be caused by lightning, thunder, and rain. Mr. Kuntz found one boloid weighing $11\frac{1}{2}$ lbs., which was in a shallow hole on plowed land; another weighing 2 lbs. 10 oz., which was lying on the surface in a pasture; and a third weighing about $9\frac{1}{2}$ lbs.

Mr. Rochus Steiner, living in the northwest quarter of Section 26, Township 137, Range 92, made a written record of the fall. According to his notes it was 10:39 P.M., Sunday, June 30, 1918. He noticed first a bright light for one-half minute; then there came a sound like rolling thunder which shook the windows of the house, followed by a whistling like that of a bullet. He found a broken meteorite partly buried 5 or 6 inches in the loose earth at the roadside, the pieces weighing about $6\frac{3}{4}$ lbs.

Mr. Leo Kern, Section 18, Township 136, Range 92, saw the fall. He was walking home about 10 o'clock at night, when suddenly there was a bright light. At first it was like a bright shooting star; then it became a streak of fire until it burst like a Roman candle. It appeared to be coming from the southeast, falling at an angle of about 15° to the horizontal. It made a "rattling sound like an airship," and when it burst the earth all about him trembled, and the house shook with the violence of the explosion. He prudently took shelter behind a telegraph pole, as the meteorite appeared to be coming directly toward him. After the explosion he heard pieces flying through the air like whistling bullets, and pieces rattled against the roof of his barn, where he found some later. After the meteorite had burst there

appeared to be a trail of "smoke or steam" in the line of flight. Several specimens were found by his daughters, Misses Emma and Irene Kern, and contributed by them to the collection of the University of Minnesota.

Mrs. Nell F. Rodenbour, postmistress at Lemmon, South Dakota, writing February 25, 1919, describes the fall as follows:

> I saw this meteorite myself and can only describe it thus: At about 11 o'clock at night we heard a dull roar like thunder, and we all ran out of the house to see, and there appeared a bright flash of light across the whole sky. It fell to the northwest, more north, and left a tail of light which remained for fully fifteen minutes.

Lemmon is about 45 miles south and 8 miles east of the place where most of the meteorite fell.

Mr. N. R. St. Marie, of Hettinger, North Dakota, wrote on February 27 as follows:

> The writer was lucky enough to get an almost perfect view of the meteorite. I was seated in an auto sky-gazing, when it attracted my attention as a shooting star. In a moment I saw that it was out of ordinary. Starting from very high it fell rapidly earthward, a little to the east of north, about 10 or 15 degrees, I judged. As it came down it illuminated the landscape to almost the brilliancy of sunlight, but the light was first of a green and later of a yellow hue. A faint whistling was discernable to part of our party; others, however, said they didn't notice any sound.
>
> I was 65 miles south and 15 miles west of Hettinger at the time.

In answer to further inquiry, on March 1, 1919, Mr. St. Marie added:

> I first noticed it very high in the heavens giving the appearance of being nearly over me; as it approached the earth it appeared more and more to the northeast.

This observer was 100 miles south and 30 miles west of the locality of the fall at the time.

Mr. Lewis Loran, Section 33, Township 137, Range 92, found several specimens of the fall, and was a witness of the phenomena. On December 12, 1918, he wrote the following detailed description of the fall:

> It was June 30, at 10 P.M.; my wife and I were in my yard, and I looked at the sky and I discovered the meteor. It was as large to me as about two

inches in diameter, and it was just where the sun is about the first week in November at fifteen minutes after twelve. It came nearer and nearer, and larger and larger, so at last I thought I must go out of its way or it would strike me. It was at least as big to me as the sun is sometime in August when it sets, but more than three times as light; then it flashed out (it was a cloudless night and no wind), and it was all still. I said to my wife, "Where is it now? It has to come. It is so near to the surface of the earth." It just took this long to say these words when we heard a great racking in the air in the same direction, and in a few seconds we heard the pieces sounding through the air like shells. We could hear that there were some smaller and some larger pieces, and that some went beyond us and some fell south of us. But the worst racking and noise was the exploding in the air. It seemed that it shook the ground under my feet, and I could hear the windows in my house rattle. We could not see the pieces, but we could hear them, and we could tell that they came from the direction from which the meteorite came.

The light of the meteor was seen over more than 400 square miles, and the noise was heard over 250 square miles.

The following account of the fall was written by Mr. Orris W. Roberts, meteorologist, United States Weather Bureau, Bismarck, North Dakota:

This meteorite was observed by the writer. I was driving my automobile some distance east of Bismarck on the night in question. As we make reports of such phenomena I am in position to give some information. The time of observation was 10:48 P.M., June 30, 1918. The meteorite appeared to move somewhat north of east and the explosion was plainly to be seen, although no report reached the observer. The light was intense, lighting up the entire sky. . . . . The location of the meteorite at the time of the explosion as located on our reports would indicate that it occurred over eastern Hettinger county.

Writing on March 19, 1919, Mr. Roberts recalled that the meteorite appeared to be falling at an angle of less than 45° to the horizontal. Bismarck is 74 miles east and 10 miles north of the locality where the meteorite fell.

There is apparent a discrepancy of about an hour between the time of fall as given by Mr. Roberts, a trained observer, and that given by almost all the other witnesses. The explanation is that Mr. Roberts, stationed at Bismarck, uses Central time, whereas the other observers quoted live west of the Missouri River, which is the geographical boundary between users of Central and Mountain time in that latitude. Mr. Roberts' estimate that

the explosion occurred over eastern Hettinger county is shown by other witnesses to be correct. The green light noted by Mr. St. Marie may have been caused by the presence of copper in the meteorite. Mr. Loran's estimate of the area over which the meteorite was seen and heard is low, because it must have been seen at a distance of one hundred miles in every direction, and the sound was heard at least fifty miles from the place of fall.

One who has read the descriptions of other meteorite falls may recognize a notable expansion with the times in the language of the witnesses. Doubtless the phenomena have been generally similar. There have been a streak of light, the noise of disruption or merely of the swift passage of masses through the air, and in some instances the whistling of smaller pieces. In early descriptions the witnesses compared the noises almost exclusively to thunder and the rolling of wagons; later came comparisons to the roar of artillery fire or the rumble of cannons, then to noises like a railway train, and to the sound of a train of cars on a bridge. The Modoc fall in 1905 perhaps is the first to have been compared to the noise of machine-gun fire, but in the descriptions of the Richardton fall the noises of small pieces are compared to that caused by the flight of shells and bullets; whereas, to describe the general noise of the fall, the witnesses introduced in comparison the motorcycle and even airships.

The Richardton meteorite is the third to be reported from North Dakota, the others being two iron meteorites: (1) at Jamestown, Stutsman County, weighing originally 4,015 gm., found in 1885, date of fall unknown; and (2) at Niagara, Grand Forks County, weighing 115 gm., found in 1879, date of fall also unknown. Richardton is the only fall which has been reported as seen to fall in North Dakota, and it is by far the largest found in the state. Of the three meteorites, the only one preserved in collections of the state is Richardton. Two representative boloids, weighing 2 lbs., and 12 oz., respectively, are at the state university. Both the Jamestown and the Niagara meteorites are widely distributed throughout the collections of the world. In this connection it may be urged that finders of meteorites should try to have a representative of every fall placed on exhibition some-

where, preferably at the state university museum, within the state in which it fell. In this way some of the public would become familiarized with meteorites, their general appearance, and their nature. The work of the collector and scientific investigator would be lightened if the finders of meteorites could be deterred from believing that meteorites contain gold, silver, platinum, radium, and other rare metals in large quantities, and from investigating meteorites with sledge hammers.

With the help of Professor W. O. Beal, of the department of astronomy of the University of Minnesota, the azimuth and vertical angle of the fall of the meteorite have been computed, using the description of Mr. Loran.

In Mr. Loran's position at 12:15, the true local time is 12:45 P.M., at which time the sun is 12° W. of S. In his latitude on the seventh day of November the sun is at an elevation of 27° above the horizon at noon. Thus, according to Mr. Loran the meteorite fell in a direction 12° E. of N., making a vertical angle of about 27° with the earth's surface.

Mr. St. Marie, 100 miles to the south and 30 miles west of Mr. Loran, thought the meteorite started to burn immediately above him. His bearing from Mr. Loran was 17° W. of S., showing that Mr. Loran's estimate of 12° W. of S. must be nearly correct. Furthermore, Mr. St. Marie estimated the direction of flight as from 10° to 15° E. of N. Mr. St. Marie and Mr. Loran were 104½ miles apart at the time of their observations, representing the locations of the incipient incandescence and the landing of the meteorite. If the meteorite fell in a straight line the altitude of the meteorite when it started to burn was at least 54½ miles above the earth's surface, allowing 1½ miles for the earth's curvature. This height should be increased probably to at least 60 miles because the meteorite probably did not fall in a straight line, but rather in a parabolic curve, although there are no data recorded about that except Mr. St. Marie's note that the meteorite appeared to fall progressively more toward the east. It seems safe to say that the meteorite started to burn at a great, but not an unusually great, height above the earth. Heights of 40 and 100 miles bound the region in which meteorites commonly start to burn.

At a height of 60 miles above the earth the air is extremely thin, indicating that the meteorite entered the atmosphere at a very high velocity, otherwise it would not have developed enough friction with the air to cause combustion. The meteorite fell near latitude 46° 30′, in June, at approximately 10 P.M., at an angle of 27° to the surface, going northward, from which data it follows that the meteorite was falling toward the sun when it was intercepted by the earth. Falling at an angle of about 90° to the course of the earth, the meteorite entered the earth's atmosphere at neither the highest nor the lowest velocity possible relative to the earth. In other words it fell neither directly opposite to the earth's flight, the condition of maximum velocity, nor did it catch up with the earth, a condition of minimum velocity. However, a meteorite falling toward the sun at the distance of the earth's orbit commonly has a velocity of 25 miles per second. By the earth's attraction the velocity might have been increased to 30 miles per second. It seems a conservative estimate to call the velocity of the meteorite when it entered our atmosphere about 30 miles per second.

The general unbroken condition of most of the examples of the fall, in spite of their brittle nature, indicates that the meteorite struck the earth's surface at a relatively low velocity. It is not clear why a meteorite should become incandescent in a very tenuous atmosphere, 60 miles above the earth, and then why its broken fragments after disruption in much denser air should not burn, unless the velocity is decreased enormously during its passage through the air. The meteorite must have passed through at least 117 miles of air from the time it commenced to burn until it reached the earth. This thickness of atmosphere appears to have offered enough obstruction to the passage of the meteorite to reduce the velocity from probably about 30 miles per second to something much less. All this, of course, is quite in accordance with commonly accepted notions as to the general behavior of meteorites. If anything, the height at which the meteorite is estimated to have commenced to burn is somewhat low for the velocity postulated. However, the general probability of the conclusions reflects most creditably upon the accuracy of the observations of both Mr. Loran and Mr. St. Marie.

Although after explosion it seems that the meteorite was not incandescent, it certainly was fused additionally; for all the surfaces freshly exposed by the main disruption were completely fused over by the time the fragments reached the earth. To such an extent was that accomplished that it is not quite certain to the writer that all the material discovered entered the atmosphere as parts of a single mass. Many of the smaller pieces, particularly, appear as if they may be units of a shower. Among the smallest pieces certain specimens show clearly three degrees of fusion. All the specimens from the northern part of the locality are covered with a thick, well-fused crust. Only the small pieces from the southern part of the area have slightly fused surfaces. These small pieces went through at least 5 miles less of the atmosphere than the thoroughly fused pieces, and some of them, at least, are fragments of a second disruption which must have occurred very near the earth. Presumably the small pieces fell first because they offer more areal resistance to the atmosphere per unit mass than the larger pieces.

Unquestionably atmospheric obstruction is responsible for the fusion and disruption of the meteorite. Disruption is commonly ascribed to shock of impact with the air, and to the disruptive effect of heat. The heat, however, probably penetrates a very little distance beyond the crust of actual fusion and combustion, and the character of meteorite ruptures certainly is not like that due to the spalling of heated surficial masses. In most cases meteorites are broken through the main mass, rather than shelled off in the familiar manner of insolation spalling of massive rocks. In the case of the Richardton meteorite, rupture was facilitated in places by the presence of metallic and troilite veins, which are planes of weakness. Several specimens are bounded partly by more or less fused metallic vein matter.

The question arises as to why the light of the meteorite ceased with its disruption. The disruption of the meteorite is described as an explosion, but this is probably a poor choice of words. There is apparently nothing in the meteorite capable of causing an explosion; but if it had exploded, part of the mass would have continued at a higher velocity relative to the air and part at a speed less than that previous to its explosion. The fact is that

the light ceased after disruption, proving that the velocity was lessened rather than increased, and indicating that the meteorite fell apart but did not explode. Such a disruption, of itself, should not decrease the velocity of flight, and except for the influence of the larger surfaces exposed, before noted, the meteorite fragments should have continued to burn after disruption as before. The fact that they did not burn again indicates that the velocity of the meteorite was so decreased at the time of disruption that the exposure of intensely cold surfaces from the interior of the meteorite, added to the increased damping effect of the atmosphere on larger surfaces, was sufficient to prevent the intense temperatures necessary for burning. Thereafter, the velocity of the meteorite must have decreased progressively as it entered denser and denser air until it reached the surface. Although not heated enough by this obstruction to burn brightly after disruption, the meteorite certainly was heated enough to cover the larger pieces with a heavy fused crust, and to form a thinner crust on the smaller pieces. The smaller pieces had a thin crust both because they went less rapidly than the larger pieces through the air, and because they went a shorter distance through the atmosphere after disruption.

Many residents of the district in which the meteorite fell have assisted greatly in collecting data and specimens. In addition to those especially mentioned above, Mr. John Muggli, of Richardton, has extended many courtesies and has given much help. Mr. W. A. Force, of the Photo Art Shop, Minneapolis, has given of his time and experience in securing the photographs from which the illustrations are made. Funds and opportunity to investigate the phenomena of the fall and to collect specimens for the museum were provided by the University of Minnesota.

A new fall has been named, classified, and described. The phenomena of fall have been reported more fully than usual, and certain conclusions in regard to the direction of flight, velocity, and consequences of disruption of the meteorite seem to follow reasonably. The meteorite is noteworthy for the concentration of metallic iron and nickel and iron sulphide in veins. The discovery of visible, metallic copper in a meteorite is announced.

PRE-CAMBRIAN ROCKS OF SOUTHEAST NEWFOUNDLAND[1]

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The following paper gives the more important results of an investigation based upon field work carried on during the summers of 1913 and 1914.

Southeastern Newfoundland is important geologically in that it affords, as far as is known, the most complete section of the later pre-Cambrian rocks along the eastern coast of North America, and an understanding of this section should aid in the correlation of the later pre-Cambrian at other localities. The term later pre-Cambrian, as here used, is possibly the equivalent of the terms Proterozoic or Algonkian.

LOCATION AND GEOGRAPHY

The Avalon Peninsula (Fig. 1) forms the southeastern portion of Newfoundland and is attached to the main island by a narrow, rugged isthmus, in places but three miles wide, which separates Trinity Bay on the north from Placentia Bay on the south. The peninsula itself is in turn almost split in twain again by St. Mary's and Conception bays. The major portion of the rocks here described lie along the eastern side of Conception Bay, at the head of this bay, and in the vicinity of St. John's; but they are believed to be typical of the entire peninsula and of the later pre-Cambrian rocks of eastern Newfoundland in general.

Except for the mining industry conducted on a large scale at Great Bell Island in Conception Bay, fishing is almost the sole occupation of the inhabitants. As a consequence of this and of the unfavorable character of the interior of the peninsulas, habitations

[1] Thesis presented to the faculty of Princeton University for the degree of Doctor of Philosophy.

are confined almost exclusively to the shore lines, and often to small valleys at the mouths of brooks which may be from a fraction of a mile to several miles apart.

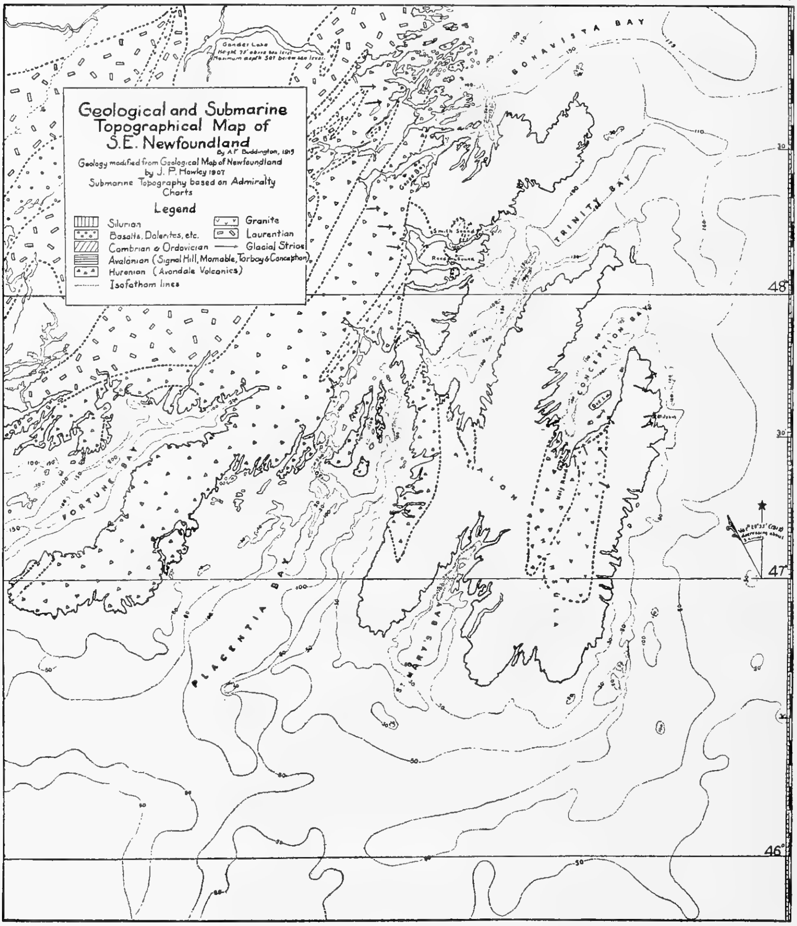

FIG. 1

LITERATURE

The literature on Newfoundland pre-Cambrian geology is well summarized by Van Hise and Leith (1909). Jukes (1843, p. 51) first separated the Cambrian from the pre-Cambrian and noted the

unconformity existing between them. He was followed by Murray (1881), who gives accurate descriptions of the pre-Cambrian sediments and classes them as the intermediate series, possibly equivalent to the Huronian of Canada. Walcott (1899, p. 219) proposed the name Avalon for the terrane lying between the basal beds of the Cambrian and the Archean gneisses of Newfoundland. Walcott (1900) described a new pre-Cambrian terrane conformable above the Signal Hill series, which he called the Random and included in the Avalon terrane. Howley (1907) published a map in which he outlined the distribution of the Avalonian series and also distinguished a formation composed of interbedded volcanics and aqueous deposits, which he separated from the base of the Avalonian terrane and called Lower Huronian. The succession worked out by Murray and Howley, the addition by Walcott, and the modification proposed by Howley are given below.

		Feet
Random	Sandstones, quartzitic sandstones, and sandy shales	1,000
Signal Hill	Red conglomerate	500
	Dark-red sandstones	1,320
	Greenish or gray fine-grained sandstones	1,300
Momable slates	Dark-brown or blackish slates	2,000
Torbay slates	Green, purple, pinkish, or red slates	3,300
Conception slates	Greenish slates	
Lower Huronian	Mixed igneous and aqueous deposits in a highly metamorphosed condition	

PHYSIOGRAPHY

In general, the striking features of the Avalon Peninsula are the parallel lineaments of the topography; the ever-present, bold, rocky cliffs of the coast; the flat-topped uplands with innumerable lakes and ponds (Jukes counted 153 from the top of Powder Horn Mountain); and the fiord bays with their deep interiors and shallower thresholds.

The topography is that of a much-dissected plateau at an altitude of from 500 to 700 feet, with monadnocks rising to heights of 1,000 to 1,100 feet, and submerged river valleys deeply gouged by glaciers and invaded by the sea, constituting fiord bays and their arms. The remnants of two definable peneplains may be represented in the present topography: one on the highland peneplain

of the plateau surface (Fig 2), the other represented in the broad river valleys and lowlands at a height of 250 to 300 feet.

The trend lines of the more impressive and marked physiographic features have been controlled for the greater part by the presence of ancient fault and fracture lines, which have to a large extent determined the distribution of the underlying rocks, with their varying degrees of resistance to erosion and weathering and the consequent parallel lineaments of the present topography. Joints have certainly played a prominent part in localizing the erosive agents.

FIG. 2.—Highland peneplain on granite; interior of the St. John's Peninsula; about eight miles east of Holyrood.

An uplift of the land following the period of glaciation is indicated by several facts. The amount of this uplift has been stated by Daly (1891, pp. 257–58), judging from the lower limit of undisturbed glacial erratics at St. John's, to be about 575 feet; but the presence of perched bowlders in precarious positions on the tops of hills at much lesser elevations (especially at about 300 feet) around Conception Bay renders this estimate of doubtful value.

GLACIATION

The results of glaciation expressed in the present topography point to the presence of local ice caps flowing into the individual bays in a direction perpendicular to the major outlines of the bays

at each point, and hence controlled in a great degree by the gross features of the pre-glacial topography. The directions of ice movement are easily decipherable from the abundant striations, the stoss and lee sides of hills (Fig. 3), and numerous bowlder trains which may be traced to their source.

Every bay indenting the coast of the Avalon Peninsula presents all the essential characteristics of a fiörd, such as high, steep, straight, parallel walls, threshold across its mouth, and small, insignificant streams entering its head. In Trinity Bay (Fig. 1) the inner, deepest portion is over 1,100 feet deeper than the sill across the mouth. Where the relations are known there is a remarkable parallelism between the strike of the major fault planes and

FIG. 3.—Glaciated hills with lee and stoss sides southeast of Harbour Main, Conception Bay. Lee sides are on the north-northeast ends of hills.

the trend of the coast line, but the writer could find no evidence that faulting was directly responsible for the formation of the fiords. The faults and fractures controlling the lineaments of the bays are of ancient date—older than the peneplains—and their influence on the present topography has been indirect. The formation of the sills across the mouths of the bays by deposits from currents is improbable, since this theory will not hold for the inland fiords of Gander Lake, Red Indian Lake, or Grand Lake, the latter with its deepest part not less than 988 feet below sea-level and with its outlet 116 feet above sea-level. In view of these conditions glacial overdeepening of river valleys probably associated with some submergence followed by the invasion of the sea seems the best-adapted explanation for these fiord bays

GENERAL GEOLOGY

The later pre-Cambrian beds have undergone at least two periods of folding, one at the close of the later pre-Cambrian, possibly the Penokean revolution, as defined by Blackwelder (1914), the other the Taconic. As a consequence of this, and of probable later movements, the beds are much disturbed, more or less closely folded, and very considerably faulted. The core of a major anticline composed of complexly faulted and folded beds of the volcanic series, cut across at a small angle by a stock of granodiorite, is exposed at the head of Conception Bay. At Chapel Cove its eroded surface is overlain by beds constituting the south end of a northward-pitching synclinal fault block of Cambrian sediments, in which Conception Bay is excavated. We have here apparently the phenomenon of the location of a younger syncline in sediments deposited in a basin on the eroded crest of an anticline.

Cutting across the east flank of the anticline is a batholith of granite forming the backbone of the St. John's Peninsula and called by the writer the Holyrood granite batholith. This is bordered on the east by a narrow band of the volcanics overlain by successively higher beds involved in minor folds until the trough of a major syncline in the Signal Hill series is reached east of St. John's. According to Murray and Howley's map of 1881 the Carbonear Peninsula is formed of later pre-Cambrian beds which overlie the volcanics and are involved in two major synclines in the troughs of which the Signal Hill series appears, with an intervening anticline on the core of which the Torbay series appears. The Placentia Peninsula, according to the same map, is composed of a syncline of beds in the trough of which the Signal Hill series lies, while the volcanic series forms its western border and appears on the flank of an anticline.

Metamorphism, although not extreme, has yet affected the rocks to a considerable degree. The beds lie in folds which, although probably not closed, yet approach that state, and a slaty cleavage at an angle to the bedding is prevalent throughout the entire bedded series. Along localized zones basaltic flows and breccias have been changed to chloritic schists, and rhyolite flows have been analogously altered to pinite, quartz-pyrophyllite, or pyrophyllite

schists (Buddington, 1916). Yet the granite, granodiorite, and many of the volcanics show little or no affects of metamorphism and are quite unaltered.

Whereas metamorphism has been a moderate factor, however, faulting on a tremendous scale and often of remarkable intensity has been the predominating feature of the diastrophic processes. These faults trend in the main a little east of north, and the throw along many of them is measurable in thousands of feet. A few of the more important ones are the fault between the Cambrian and pre-Cambrian along the east side of Conception Bay from Topsail to Cape St. Francis, with a throw of 8,000 feet, as determined by van Ingen; the fault a short distance inland from the west side of Colliers Bay in Conception Bay, which may be traced for almost ten miles and separates the Cambrian from the pre-Cambrian and the Conception slates from the volcanic series; and lastly, the fault on the west side of Random Sound, which may be traced for fifteen miles and brings Cambrian beds against pre-Cambrian granite and the Conception slate series.

UNCONFORMITY BETWEEN CAMBRIAN AND LATER PRE-CAMBRIAN

The uncomformable relations of the Lower Cambrian beds to those of the later pre-Cambrian, with the possible exception of the Random formation, can be definitely established. At eleven widely separated localities in Conception Bay the actual unconformable plane of contact between the Lower Cambrian and the later pre-Cambrian may be observed.

At Brigus the Lower Cambrian rests with an angular unconformity on the upturned beveled edges of members of the Avondale volcanic series. Along Colliers Bay the Lower Cambrian with a gentle dip rests unconformably on more or less vertical basalt flows and breccias of the Avondale volcanic series. At Chapel Cove the Lower Cambrian beds rest on the eroded surface of a quartz syenite and contain pebbles of the underlying rock. At Duff's Station the Lower Cambrian overlies granite, occupying hollows and filling deep, narrow wedgelike spaces between joint planes so as to resemble a network of veins on the surface. At Upper Gullies it rests with unconformable relations on a gabbro mass. On Kelligrews Brook

a chloritized granite gneiss is overlain by Cryptozoan limestone beds of Lower Cambrian age. Just west of Manuels three exposures of the unconformable relations are presented. At the first locality limestone rests unconformably on granite and on a rhyolite dike in the granite. A shale bed of Cambrian age overlaps the limestone and also rests directly on the granite and contains pebbles of it. A near-by conglomeratic limestone consists almost entirely of cobbles of rhyolite similar to the rock of the rhyolite dike. At the second locality a deep-fissure deposit of conglomeratic limestone with pebbles of the country rock occurs in diabase. At the third locality a Lower Cambrian conglomeratic limestone carrying Hyolithes and Coleoloides rests on dark-red rhyolite, the pebbles consisting almost entirely of the underlying rock. Again, in the bed of Manuels Brook a coarse conglomerate rests unconformably on volcanics and on a granite dike intrusive in the volcanics. The conglomerate is of Lower Cambrian age and consists of cobbles and bowlders of the underlying granite and volcanics.

On Trinity Bay, along Smith and Random sounds, the Lower Cambrian, of older age than that on Conception Bay, rests disconformably on beds of the Random formation in the trough of a syncline. The Random may be either conformable or disconformable with the Signal Hill series. In either case the Lower Cambrian must be unconformable with the Signal Hill series and all lower formations, since it must necessarily have transgressed all the later pre-Cambrian formations in passing from its disconformable position on the Random, the youngest formation of the pre-Cambrian, in the trough of a syncline, across the flank of an anticline on to the lowest later pre-Cambrian formation, the Avondale volcanics, on the core of an anticline in Conception Bay.

AVONDALE VOLCANICS

Howley (1907) mapped a series of rocks which he called Huronian and described "as composed of mixed igneous and aqueous deposits in a highly metamorphosed condition." Parallel to their trend they are mapped by Howley as outcropping for a distance of about two hundred miles in a north-northeast-south-southwest direction, being submerged beneath the sea at each end.

In view of the unknown age of this formation, and because of its characteristic development and typical outcrops in the vicinity of Avondale, Conception Bay, the writer proposes the name Avondale volcanics to designate this series, which comprises rocks of direct volcanic origin, together with a small amount of interbedded more or less waterworn volcanic materials. They constitute a formation of wide geographical extent—200 miles along the strike and 100 miles or more across the strike—and of great but unknown thickness, at least several thousand feet, forming so far as is known the basal member of the later pre-Cambrian or Avalonian system of Newfoundland. Interbedded rhyolite and plagioclase basalt flows, with corresponding breccias, crystal, lithic, and vitric tuffs, volcanic dust beds, and average tuffs, together with volcanic conglomerates, sandstones, and slates are comprised within the series.

The beds are in a highly disturbed condition, with a prevailing steep dip, and are affected by intense and often profound faulting. They are exposed on the cores of major anticlines or are brought to the surface on the upthrow sides of great faults. The degree of metamorphism which the rocks have suffered is in general moderate, though locally intense, and is manifest for the larger part merely in the development of a slaty cleavage. Secondary minerals, except those of surface origin, are confined almost exclusively to sericite and quartz in the acid rocks and chlorite with sericite, epidote, and calcite in the basic rocks. Along certain shear zones in the acid rocks pyrophyllite, quartz-pyrophyllite, and pinite schists have formed through replacement, while in certain basic rocks copper ores have been deposited along close-set narrow fractures and in vesicles of the flows. Ore in quantities of commercial importance, however, has not yet been found.

In view of the great age of the rocks the lack of intense metamorphism and the frequent preservation of delicate primary structures are striking. Indeed there is little doubt that, with search, practically every structure and texture found in the Tertiary and recent volcanics might also be found in these ancient pre-Cambrian volcanics.

One of the most interesting discoveries in this series was the presence of volcanic necks intruded through the breccias and tuffs.

Near Manuels a plug of plagioclase basalt about 400 by 450 feet, with columnar jointing perpendicular to the surface and with dikes and apophyses radiating from it into the adjoining rocks, was found intruded through basaltic and rhyolitic breccias. A rhyolite neck about fifty feet in diameter and circular in shape, nearly every foot of the contact of which could be seen, and a neck of basic tuff with fragments up to three feet in diameter of the underlying rocks, through which it was drilled, and with radiating dikes of tuff, were also found. The largest neck forms a conspicuous hill about three miles south of Holyrood and seems to have been one of the main centers of volcanic activity in this region. Here we find a great elliptical stock of rhyolite porphyry about a mile long and half a mile wide, while in the surrounding country occur exceptionally coarse rhyolite breccias, with many blocks up to two feet in diameter, interbedded with rhyolite flows and tuffs. A chemical analysis of this rock, given below, shows it to be very similar to the rhyolite flows at Manuels.

TABLE I

Chemical Analysis of Rhyolite Porphyry from Volcanic Neck South of Holyrood

SiO_2	75.85	K_2O	4.47
Al_2O_3	13.03	H_2O+	.35
Fe_2O_3	1.82	H_2O-	.05
FeO	.32	MnO	.05
MgO	.05		
CaO	.38	Total	99.71
Na_2O	3.34		

The rhyolite flows are quite variable in color, ranging through reddish, purplish, and greenish grays. They are usually aphanitic in texture, and dense, chertlike in character, sometimes felsitic, with a finely rough feel. They may be homogeneous and massive, or may be marked by beautiful, well-developed, and well-preserved banded textures, and are very frequently spherulitic. The spherulites vary from microspherulites up to those as large as a man's head, or even occasionally attain a diameter of two feet (Fig. 4), but in general they are of medium size (Fig. 5). The flows may also be characterized by a platy jointing more or less parallel to the flowage planes, or by flow breccia, eutaxitic (Fig. 6), or perlitic structures.

As seen in thin section the texture is usually microgranitic or an irregular polarizing aggregate of quartz and feldspar. Spherulitic, axiolitic, and microspherulitic textures are common, and rarely a felt of microlitic feldspars in a groundmass of quartz is observed. A micrographic texture characterizes portions of an eutaxite from

FIG. 4.—Very coarsely spherulitic rhyolite; the largest spherulite is twenty-two inches in diameter; about five and one-half miles south of Manuels, Conception Bay.

near Avondale. A chemical analysis of a specimen from a 50-foot rhyolite flow follows. The rock is a dense, red, banded felsite with a microfelsitic to finely microcrystalline and micropoikilitic texture.

TABLE II

CHEMICAL ANALYSIS OF RHYOLITE FROM FLOW AT MANUELS

SiO_2	76.24	Na_2O	2.55
Al_2O_3	13.94	K_2O	4.95
Fe_2O_3	.89	H_2O+	.15
FeO	.13	H_2O-	.03
MgO	.27		
CaO	1.07	Total	100.22

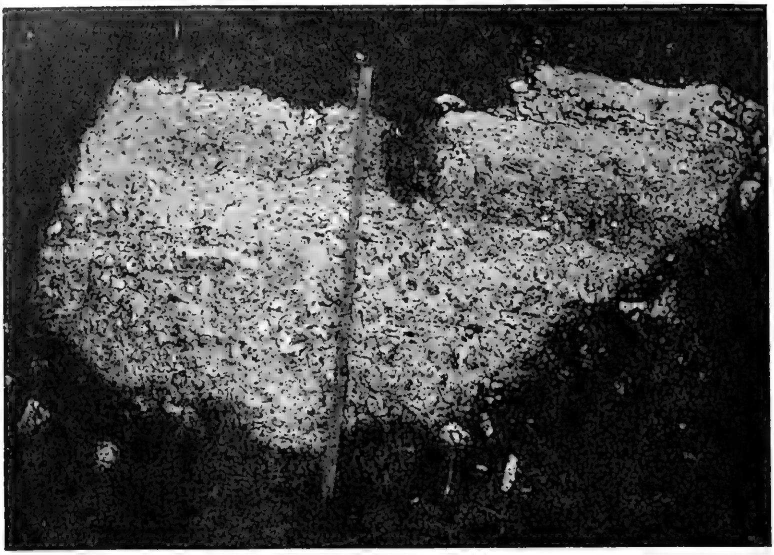

FIG. 5.—Medium spherulitic banded rhyolite; about five and one-half miles south of Manuels, Conception Bay. Photograph by G. v. I.

FIG. 6.—Microphotograph of eutaxitic structure in rhyolite. Hill 467, south of Avondale, Conception Bay. Natural light, ×32 diameters.

Basalts attain a tremendous development along Colliers Bay, extending south toward Brigus Junction. They are associated with a great development of basaltic breccias and often exhibit amygdaloidal or flowage structures. The flows are very much altered throughout and may be chloritized with resultant green-gray rocks, or hydrated and thoroughly impregnated with iron oxide giving purplish- or reddish-brown hues. These alterations are probably due to thermal waters, as they occur independent of what

FIG. 7.—Coarse rhyolite breccia; about two and one-half miles south of Manuels, Conception Bay. Photograph by G. v. I.

might be expected as the result of weathering. In texture they vary from felsitic to finely porphyritic, and in thin section show a felt of plagioclase laths or microlites with a distinct fluxion structure in a chloritic or indistinct altered groundmass. Chlorite pseudomorphs, replacements of some ferromagnesian mineral, possibly augite, occur as abundant minute phenocrysts in some flows.

The breccia beds exhibit a varied assortment of colors and a wide range in the diameter of their component fragments; but by far the predominant portion of the rhyolitic breccias are various hues and tones of reddish- and purplish-gray, whereas the basaltic breccias

consist of dark greenish-gray fragments in dark reddish-, purplish-, or greenish-gray matrices.

Both basaltic and rhyolitic breccias exhibit approximately the same range in the diameter of their fragments, from a fraction of an inch to four feet (Figs. 7 and 8). The general run of the fragments

FIG. 8.—Coarse basalt breccia; west side of Blue Hills, south of Conception Bay

would probably average a few inches in diameter. In general, the rhyolitic breccias and the basaltic breccias contain few foreign fragments, especially the coarser beds; yet beds in which angular fragments of rhyolite and basalt and crystals of orthoclase and plagioclase are mingled are frequent; and rhyolitic breccias and basaltic breccias are often found interbedded.

Crystal tuffs are of frequent occurrence interbedded with the breccias and tuffs. They are remarkable, in view of their great age and the vicissitudes which they have undergone, for the frequent presence of a perfectly preserved vitroclastic structure in their groundmass, whether rhyolitic or basaltic in nature. These devitrified glass shards are such a prominent feature of some of the tuffs from the vicinity of Red Rock Lake near Brigus that they

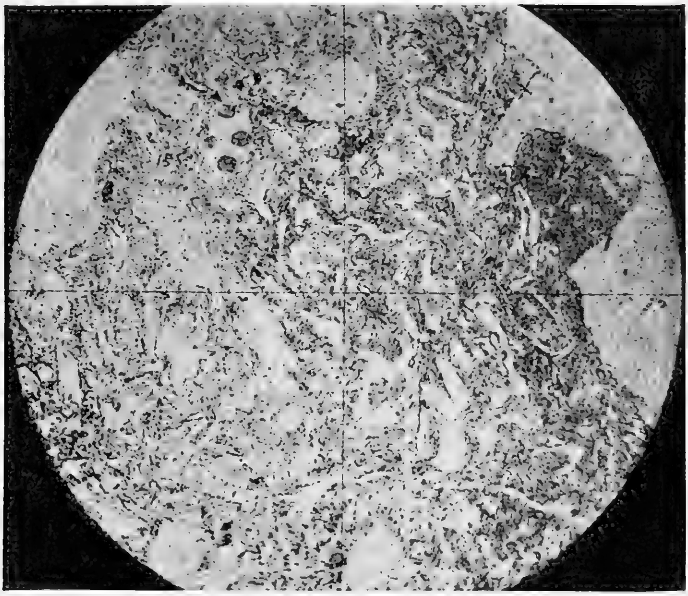

FIG. 9.—Microphotograph of vitroclastic groundmass of rhyolitic crystal tuff; near Red Rock Lake, south of Brigus, Conception Bay. Natural light, ×56 diameters.

might well be denominated vitric tuffs (Fig. 9). In other cases the groundmass is an indistinct, microcrystalline, granular dust. Many of these tuffs are soaked with hematite and hence are reddish in color. Associated with the phenocryst-like crystals are fragments of either porphyritic or felsitic basalt or rhyolite, or of devitrified obsidian exhibiting trichites, microspherulites, spherulites, axiolites, perlitic cracks, pumiceous structure, or any combination of these. The crystals consist principally of plagioclase and

orthoclase, with quartz and magnetite in the acid tuffs, and of plagioclase, augite, magnetite, apatite, and foreign crystals in the basic tuffs. Some of the basic tuffs resemble typical palagonite tuffs (Fig. 10).

The lithic tuffs consist predominantly of fragments of rhyolite or of pilotaxitic basalt, according to their nature, in a groundmass

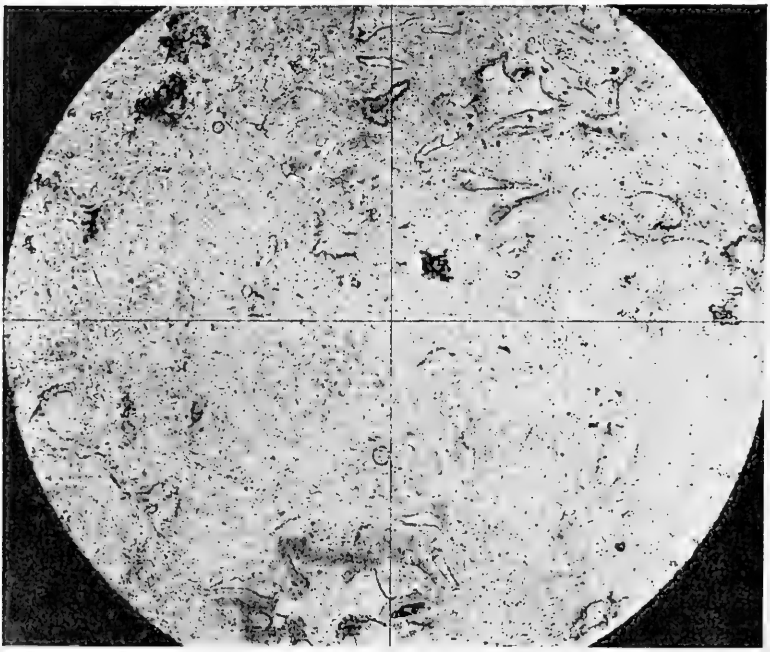

FIG. 10.—Groundmass of basaltic crystal tuff, with devitrified shards of glass bordered by rims of fibrous, brownish material. Hill 937 near Holyrood. Microphotograph. Natural light.

consisting of finely comminuted materials similar to the lithic fragments, with crystals of feldspar and quartz in minor amount. The volcanic-dust beds are frequently well bedded and chertlike in character, often translucent in thin edges, with a conchoidal to subconchoidal fracture.

The waterworn volcanics comprise volcanic conglomerates, sandstone, and a rare red shale bed. The prevalence of volcanic

conglomerates, both stratigraphically and geographically, interbedded with the volcanic breccias, flows, and tuffs, is one of the most cogent arguments for the subaërial origin of the volcanic series as a whole; for both basalt and rhyolite conglomerates are associated with and interbedded between completely angular basalt breccias and well-rounded basalt conglomerates, and between similar angular rhyolite breccias and well-rounded rhyolite conglomerates. In some of the basalt conglomerate beds bowlders up to three feet or

FIG. 11.—Basalt volcanic conglomerate; Turks Gut, Colliers Bay, Conception Bay. Photograph by G. v. I.

more in diameter are not rare (Fig. 11). Such beds are in places 200 feet thick and grade upward or downward into sandstones or tuffs. Some of the sandstone beds are cross-bedded and contain abundant fragments of red shale constituting typical thon-gallen beds. Others are ripple marked, but these features are rare.

In the course of the work no reasons were found for assuming the volcanics to have had other than an essentially subaërial origin. All the structures and textures of the flows and the characters of the associated volcanic products are compatible with such a hypothesis, while the particular criteria pointing to such a conclusion are as follows:

The predominance and widespread distribution of the red and brown volcanic tuffs and breccias, which owe their color to saturation and cementation with hematite, point toward subaërial exposure rather than toward local effects of volcanic gases.

The constant association of volcanic conglomerates or sandstone with the breccias, tuffs, and flows indicates the work either of river erosion, or wave work, or both. The first seems more probable in view of the constant recurrence of conglomerate beds in the stratigraphic succession, as well as the fact that beds of conglomerate 150 to 200 feet, thick with well-rounded bowlders up to three feet in diameter, are exceptional within marine deposits, even within marine volcanic deposits. On the other hand such conglomerates are commonly found associated with subaërial volcanics of all ages. Those of Newfoundland are such as might be expected to form along river valleys draining a region of great active volcanic cones such as this probably was. Although some of the conglomerates may have been deposited in standing water, the indications are that for the most part they were deposited on a land surface during quiescent periods between successive volcanic outbursts which repeatedly buried them with the products resulting from extravasation and explosion.

The volcanics are, so far as known, the oldest formation of the later pre-Cambrian in this district. They are intruded by granite, and together with the granite are overlain unconformably by Lower Cambrian sediments. The pre-Cambrian volcanics of the Blue Ridge of Virginia and Maryland present similar relationships (Keith, 1892), and in the present state of knowledge it seems probable that in early later pre-Cambrian times a chain of volcanic cones extended from Newfoundland to North Carolina and farther, in a zone more or less parallel to the present coast line.

CONCEPTION SLATE SERIES

The Conception slate series was examined by the writer along the east side of Conception Bay from Portugal Cove to Topsail; along the west side, Colliers Bay north to Brigus; near La Manche on the Isthmus of Avalon; and along Smith and Random sounds on Trinity Bay. Owing to folding, faulting, and covered exposures

the relations of this series to the beds above and below were not seen.

The series consists predominantly of thin-bedded, green-gray, dense, hälleflinta-like slates, at least several thousand feet thick, which may be compact without cleavage, or dynamically metamorphosed, with a resultant well-developed cleavage; and to a lesser extent of green-gray feldspathic sandstones and conglomerates. The slates often resemble at a superficial glance banded flow rhyolites, but occasional sandy layers betray their true origin.

The slates may vary from very fine-grained or dense siliceous quartzites to argillaceous slates, or from dense feldspathic quartzites to chertlike feldspathic slates. Thin, intercalated beds and layers of feldspathic sandstone are common, but the predominant character of the rocks is that of a slate. The feldspathic character of the typical slate and its normally fresh, undecomposed character are shown very well by the two chemical analyses which follow. It will be noted that the soda is in excess of the potash, contrary to the usual rule for sediments derived from well-weathered materials, and that the analyses resemble those of certain rhyolites. The high soda content may be due to plagioclases washed in from basic tuffs.

TABLE III

Chemical Analyses of Members of Conception Slate Series

	1	2
SiO_2	68.92	77.13
Al_2O_3	17.67	14.01
Fe_2O_3	1.43	2.25
FeO	3.48	Undet.
CaO	.85	.64
MgO	1.19	.36
Na_2O	3.01	3.59
K_2O	1.46	1.01
Ign. Loss	1.75	.76
Total	99.76	99.75

1. Feldspathic slate, near Brigus, Conception Bay.
2. Feldspathic quartzite, Robinson's Bight, Random Sound, Trinity Bay.

The sandstones are formed of angular to subangular grains of quartz, fresh plagioclase, orthoclase, rhyolite, plagioclase basalt, and tuffs. The rhyolite fragments exhibit axiolitic, spherulitic, and banded textures.

The conglomerate outcrop near La Manche, and the pebbles, are all of volcanic rocks such as basalt, basalt porphyry, rhyolite porphyry, felsite, etc., imbedded in a matrix showing innumerable flashing cleavage faces of white plagioclase.

Since these beds in their well-bedded and unoxidized characters give evidence of their being deposited beneath a permanent water-level, and since they consist almost exclusively of materials similar to the rocks comprised within the underlying volcanic series of subaërial origin, it is probable that an unconformity exists between the Conception slate series and the Avondale volcanics, and that the former are derived from the latter, at that time a more or less loose accumulation of volcanic ash and breccias which were swept into the sea in a comparatively fresh and undecomposed condition.

TORBAY SERIES

The Torbay series was not studied by the writer. Murray's description of it is inserted here for completeness:

> Green, purple, pinkish, or red slates in frequent alternations; the texture of these slates is generally extremely fine, and in some cases they approach in hardness to jasper or chert. The fracture is often conchoidal, and the imperfect cleavage parallel with the bedding; but in many instances the rock has a good cleavage at right angles to the stratification and is well adapted for roofing purposes. The exposed surfaces weather for the most part a yellowish white.

Some beds seen by the writer on the Isthmus of Avalon strongly resemble banded argillites; cobbles of green and red argillite were also found in the drift of the St. John's Peninsula, presumably derived from the Torbay series.

MOMABLE SERIES

These beds are described by Murray (1881, p. 145) as follows:

> Dark brown or blackish slates of St. John's, with ripple marks very distinctly displayed on some surfaces, and in which some obscure organic remains have been found resembling those found in c, and another supposed to be the shelly casing of some description of Annelid. The cleavage of this slate is sometimes very regular, oblique, or at right angles to the bedding, but in parts it also cleaves parallel with the stratification. Towards the top are frequent layers of hard, fine-grained, greenish sandstone interstratified, not usually over 6 or 7 inches in thickness.

The beds seen by the writer are strongly ripple-marked, blackish-gray, thin-bedded, very fine-grained, shaly sandstones, with thin films of black carbonaceous or graphitic shale. In thin section the sandstone is seen to be made up of sharply angular grains of quartz, with an occasional fresh feldspar fragment and bits of carbonaceous material. The grains average about 0.05 mm. in diameter.

From a lithologic point of view the most striking feature of these rocks is their content of carbonaceous material, which, although slight and often absent, yet serves to contrast them with the overlying and underlying formations. In contrast to the succeeding reddish-brown feldspathic sandstone formation, the gray, fine-grained quartz sandstones and shales of the Momable suggest an origin under a permanent water-level at shallow depths in which flourished organisms whose presence is indicated by the carbonaceous content of the shales and by the possible fossil Aspidella.

Attention has been called by many observers to the resemblance between the gold-bearing series of Nova Scotia and Murray's Intermediate series of Newfoundland. It is to the beds comprising the Conception, Torbay, and Momable series lying below the Signal Hill series and above the Avondale volcanics that this lithologic resemblance applies. Judging from Fairbault's descriptions (Malcom, 1912, pp. 46–47) the Goldenville quartzites present certain resemblances to the Conception slate series, the banded argillite division of the western part of the field to the Torbay series, and the Halifax formation to the Momable series. Specimens of the Halifax slate collected by the writer from an outcrop in the yards of the Canadian Pacific terminal at Halifax are indeed indistinguishable, except for a more prevalent cleavage, from many characteristic specimens of the Momable series. Before any correlation may be suggested, however, it is necessary that a more intimate knowledge of the conformable or unconformable relations within the Newfoundland series shall be known, as well as more definite information concerning the relations of the gold-bearing series of Nova Scotia to the Cambrian. The Momable beds are also similar to the Animikie sediments as described by Coleman in respect to their content of carbonaceous material.

SIGNAL HILL SERIES

As near as can be judged from the descriptions of Murray and Howley (1881) and from the experience of the writer the Signal Hill series outcrops mainly in the troughs of synclines or synclinoria over an area extending for a length of about 200 miles in a north-northeast-south-southwest direction and about 75 miles at right angles to this.

The series consists of a very thick succession of reddish-brown, occasionally green, feldspathic sandstones and conglomerates, with intercalated shale beds and about 1,300 feet of greenish-gray, thick-bedded feldspathic sandstones at the base, giving a thickness estimated at about 10,000 feet. Murray's estimate of 3,120 feet for this series referred only to the beds on the west side of St. John's harbor, which constitute but a part of the series.

Thon-gallen or intraformational conglomerate beds are abundant. The majority of the conglomerate beds may be appropriately described as gravel or pebble beds, with the pebbles varying in size from one-fourth of an inch to an inch in diameter, and prevailingly subangular to rounded.

Because of the predominating sandy character of such a thick series of sediments; the repetition and often considerable thicknesses of conglomerate beds; the presence of so much fresh plagioclase and orthoclase throughout the rocks; the prevailing subangular character of the component grains; the predominating red color due to interstitial hematitic mud, to films of hematite, and to oxidized grains of basalt, rhyolite, and magnetite; the constant recurrence of thon-gallen beds; frequent cross-bedding; lithologic alternations of sandstone, conglomerate, and shale; and the absence of any limestone, fossils, or carbonaceous materials, the writer has been led to conclude that these beds originated as dominantly fluviatile deposits of subaërial origin in a subarid climate. It is quite possible that the basal 1,300 feet of green-gray sandstones accumulated under a permanent water-level; but if so the water was apparently drawn off or excluded at the time of accumulation of the succeeding reddish-brown series.

In thin sections from specimens of deep, livid-brown sandstone from Signal Hill the rock is found to consist of angular to subangular

grains of quartz, fresh plagioclase, orthoclase, and rhyolite and granophyre, with rarely a fragment of basalt. Accessory minerals comprise grains of primary epidote and occasionally abundant grains of magnetite. A film of hematite coats each grain, and in some specimens the interstices are filled with secondary quartz, sericite, or occasionally with epidote. The sericite is a secondary product, the result of recrystallization during shearing. In one section a rounded grain of primary epidote is coated with a film of hematite and is surrounded on the outside of this by a growth of secondary epidote. The cement of the green sandstone seems to be of an epidotic nature, apparently arising through a recrystallization of an impure argillaceous material. A chemical analysis of the reddish-brown sandstone serves to confirm the highly feldspathic nature of this rock.

TABLE IV

CHEMICAL ANALYSIS OF FELDSPATHIC BROWN SANDSTONE FROM NEAR SIGNAL HILL, ST. JOHN'S

SiO_2	71.38	Na_2O	2.28
Al_2O_3	14.25	K_2O	1.99
Fe_2O_3	4.75	H_2O+	1.20
FeO	.46	H_2O-	.21
MgO	.46		
CaO	3.01	Total	99.99

That the red color of the brown sandstones is due to hematite and to the oxidation of its iron content is evident from a comparison of the ferrous and ferric contents of the red and green sandstones. Although both have similar total contents of iron, 4.74 and 5.11 per cent respectively, expressed in terms of ferrous iron, the brown sandstone shows 4.75 per cent of ferric oxide and only 0.46 per cent of ferrous oxide, whereas the green sandstone shows 2.54 per cent of ferric oxide and 2.82 per cent of ferrous oxide.

The red color of the sandstones depends in varying degrees upon the primary deposition of a hematitic mud in the interstices of the sand grains; upon the deposition of hematite as a cement around the sand grains; upon hematite existing in the grains themselves as in the cleavage cracks of feldspar, or in oxidized basalt and rhyolite; and upon the hematite resulting from the oxidation of magnetite grains *in situ*.

The pebbles of the conglomerates in the vicinity of Signal Hill consist roughly of about three-quarters rhyolite-porphyry and the remainder granophyre, intraformational red shale flakes, and quartz, with occasional pebbles of basalt. The rocks of which these pebbles are formed are very similar to the rocks comprised within the Avondale volcanic series, and it is quite possible that they have been derived from that formation.[1]

In their stratigraphic relations, lithology, and mode of origin the Signal Hill series resemble the Jotnian of Sweden, the Torridonian of Scotland, and the Keweenawan of the "Canadian Shield." In the absence of vulcanism, so far as yet observed, they stand in contrast to the Keweenawan and Jotnian, but resemble the Torridonian. This is of special interest, since it has been shown by Hayes and van Ingen that this district during the succeeding Cambro-Ordovician period had a history which coincided even in minor detail with that of Wales.

INTRUSIVE ROCKS

The later pre-Cambrian rocks, more especially the early later pre-Cambrian beds, are intruded by several batholiths and stocks of igneous rock and are very intensively cut by dikes. In general, it may be said that the salic rocks have been intruded as molten masses of batholithic or stock type, with few apophyses or dikes, whereas the older basaltic or gabbroic magmas, to a preponderating extent, have been intruded as dikes.

The rocks, with the exception of the quartz syenite and granodiorite, whose position is unknown, are given in the order of their intrusion, beginning with the oldest. Those around Conception Bay comprise hornblende granite gneiss, hornblende gabbro and plagioclase gabbro without olivine but locally quartz-bearing, basic granodiorite, biotite granite and granophyre, quartz syenite, aplite and granophyre dikes intruding the granite, and younger dikes of rhyolite porphyry and diabase intruding all the older rocks. Near

[1] Murray describes the pebbles of the conglomerate at Signal Hill as composed "chiefly of white quartz, but with occasional pebbles of brown or red jasper, syenite or gneiss and slate." The writer examined 150 pebbles with the entirely different result given above.

Clarenville on Trinity Bay a mass of gabbro is intruded by granite, and both in turn are cut by younger dikes of aplite, rhyolite, and porphyrite dikes.

The hornblende granite gneiss shows a cataclastic texture and is believed to be the oldest rock in the district. Its outcrop was noted in only three areas of very small extent along the border of the Holyrood granite batholith.

The gabbros occur as small, irregular patches on the borders of and within the area of the Holyrood granite batholith, and also as huge dikes in the Conception slate series. They are predominantly of a blackish or dark speckled gray color weathering to an ashen gray. In grain they vary from fine to medium, and pegmatitic facies are entirely lacking. Mineralogically there seem to be two types, which can be distinguished by microscopic methods alone: one characterized by hornblende without augite; the other an augite gabbro in which the pyroxene may be unaltered or partially altered to hornblende or uralite.

Microscopically the augite gabbros are found to be predominantly hypautomorphic-granular in texture, occasionally becoming ophitic. The augite and plagioclase may be fresh, or partially or completely altered; and the alteration of these minerals seems to have proceeded independently, for fresh augite may be associated with altered plagioclase, and vice versa. The plagioclase may be partially altered to sericite, or flecked with sericite and partially replaced by quartz or epidote. The augite may be partially or completely altered to compact green hornblende or to an aggregate of uralite fibers or of uralite, quartz, and chlorite. The ilmenite is usually altered to leucoxene and is very small in amount. Pyrite is rare and magnetite relatively abundant. The peak of Holyrood Butterpot is formed of an elliptical mass of gabbro about 1,200 feet by 500 feet, completely surrounded by granite. It is peculiar in having quartz in small amount filling the interstices between the feldspars in such a manner as to indicate its origin as an original constituent, the last product of crystallization. Some of the augites are twinned, and others show idiomorphic basal sections. A chemical analysis of this rock is given on page 476, No. 2.

About six miles south of Manuels, lying between a series of green slates and the Holyrood granite, a more or less elliptical-shaped mass of gabbro forms a conspicuous ridge in the topography. This gabbro has a tendency toward a gneissic structure but without any particular evidences of dynamic metamorphism. It is quite intimately penetrated by ramifying apophyses of granite and by epidote veins, which are especially common along the joint planes. In thin section the rock is seen to be hypautomorphic granular to ophitic in texture and to consist essentially of light-green hornblende and labradorite. The feldspars are extensively altered to sericite, and some of the hornblende to intergrown fibers and blades of epidote, zoisite, and quartz. Many of the hornblendes are twinned parallel to the orthopinacoid, and by an occasional resemblance of crystal form give indications of an apparently primary origin. Whether this rock is the result of recrystallization during the intrusion of the granite or whether it is primary is difficult to say. A chemical analysis is given on page 476, No. 1. In this connection it may be well to note that where the road crosses Seal Cove Brook there is an outcrop of hornblende porphyrite with phenocrysts of hornblende up to 10 mm. in length and plagioclases averaging 2–3 mm. in length. In thin section this rock is found to consist of idiomorphic phenocrysts of labradorite and hornblende in a groundmass in some places consisting of a microcrystalline, elsewhere of an almost crypto-crystalline, aggregate of plagioclase microlites, quartz, and an altered ferromagnesian mineral in sparse amount. The plagioclases show a zonary banding.

To the west and south of Woodfords is a stock of granodiorite about two miles long and one-half mile wide, intrusive into the beds of the Avondale volcanic series. Dikes from this mass are exceptionally rare, but enough evidence was found to prove its intrusive nature. The rock is light colored and medium grained, consisting of pink orthoclase, black hornblende, and quartz. The latter is abundant in small grains which show upon a fresh surface only when closely examined. On the weathered surface, however, they stand out in relief and give to the rock the appearance of a typical granite. With the microscope the rock is found to consist of andesine, orthoclase, augite, and quartz, with abundant rods and grains of apatite.

The colorless augite is almost completely altered to pleochroic green hornblende and chlorite. A chemical analysis of this rock is given on page 476, No. 3.

Outcrops of a quartz syenite are found along the shore to the north of Chapel Cove. This rock has a very limited distribution, occurring in fault blocks brought into their present position by thrusting, and in places the rock is much crushed by the stresses to which it has been subjected. In the hand specimen the rock appears to be a white, medium-grained syenite, consisting of an aggregate of feldspars averaging 5 mm. in length. In thin section the rock is seen to consist of an aggregate of plagioclase feldspars, predominantly albite and to a minor extent oligoclase, with a groundmass of quartz and orthoclase in micrographic intergrowth filling the interstices. The rock is crushed and exhibits cataclastic texture in a high degree. A chemical analysis of this rock will be found on page 476, No. 4.

The backbone of the St. John's Peninsula is mapped by Howley (1907) as Laurentian. This rock in its northern half was found by the writer to bear intrusive relations to the Avondale volcanics and to constitute a granite batholith five to six miles in width and about forty miles in length, if its boundary to the south continues to coincide with that of Howley's Laurentian area. The eastern boundary, where it was followed by the writer for several miles, is delimited by a fault plane. Along the west side the beds are very much disturbed and folded. The rock is a pink, medium-grained, equigranular, biotite granite, consisting essentially of quartz, orthoclase, albite, oligoclase, and chlorite, the latter believed to be derived from biotite. Fresh flakes of original biotite, however, are found only in occasional sections. A chemical analysis of the rock appears on page 476, No. 5.

One of the most striking and interesting features of the geology along Smith and Random sounds at the head of Trinity Bay is the way in which the early green slates of that region have been rent, riven, and intruded by a great series of approximately parallel dikes of porphyrite and basalt. At one locality there were counted 32 dikes in a distance of about 350 yards. As a rule, however, the dikes are not as frequent as this; yet they are never absent for any

great distance. Their general strike is approximately north-south. About half the dikes are between two and five feet in width, and the rest are about equally divided between dikes ten to fifteen feet and those thirty or more feet in width. In addition to the dikes in the slate series several dikes and sills were found intruding the Cambro-Ordovician rocks, and dikes in the Signal Hill and Random formations are present but rare. The porphyrite dikes are variable in their mineralogical composition and comprise hornblende porphyrites, labradorite porphyrites, and augite porphyrites or basalts.

TABLE V

CHEMICAL ANALYSES OF INSTRUCTIVE IGNEOUS ROCKS AROUND CONCEPTION BAY

	1	2	3	4	5
SiO_2	48.54	51.34	59.18	69.52	71.82
Al_2O_3	20.62	18.94	18.21	16.85	16.07
Fe_2O_3	5.39	3.29	2.73	.03	1.22
FeO	5.53	6.49	3.62	1.65	1.60
MgO	4.77	4.55	2.51	.18	.40
CaO	8.16	8.84	4.23	1.37	1.66
Na_2O	3.14	2.19	3.84	5.09	3.27
K_2O	1.23	1.09	3.26	3.73	3.07
H_2O+	1.85	2.12	1.85	.89	.71
H_2O-	.17	.11	.20	.05	.19
TiO_2	.20	.34	Undet.	.21	Undet.
MnO	.19	.29	.16	.09	.13
Total	99.77	99.59	99.79	99.66	100.14

1. Hornblende gabbro from about 6 miles south of Manuels.
2. Quartz bearing gabbro from Holyrood Butterpot.
3. Granodiorite from near Woodfords.
4. Quartz syenite from Chapel Cove.
5. Biotite granite from interior of St. John's Peninsula.

The former are found in the pre-Cambrian slates, but only the last named in the Cambro-Ordovician beds.

In the region about Conception Bay the granite of the Holyrood batholith, the gabbro, quartz syenite, and dikes of rhyolite porphyry and diabase are all overlain unconformably by Lower Cambrian sediments. Salic dikes were not found intruding beds younger than the Conception slate series, and femic dikes are far less frequent in formations above this series than in those below it and constituting it. Whether this is due to the different character of the formations, to their different stratigraphic position, or to their different age,

is an open question. What little evidence there is seems to point toward a period of batholithic and dike intrusion at a time succeeding the period of deposition of the Conception series and preceding that of the Signal Hill series. No dikes whatever were found intruding the Cambro-Ordovician beds in the region of Conception Bay, but in the vicinity of Trinity Bay infrequent dikes of a distinctive character do intrude these beds and undoubtedly belong to a younger period of intrusion, possibly that of the Taconic revolution, or related to the period of vulcanicity represented by vast flows of lava in the Notre Dame Bay region about fifty miles to the northeast. This period of intrusion during the pre-Cambrian corresponds to a similar period of intrusion of granite into the volcanic series of the Blue Ridge of Maryland and Virginia described by Keith (1892), or the Proterozoic batholiths of the Lake Superior region described by Allen (1915, p. 717) which he suggests are post–Middle Huronian or pre–Upper Huronian.

Geographically, chemically, and physically the volcanics, plutonics, and dikes of the Conception Bay region appear to be genetically allied. Thus the gabbros, quartz-bearing gabbro, hornblende porphyrite with quartzose groundmass, granodiorite, quartz syenite, biotite granite, granophyre, and aplite form a series of rocks with an ascending silica ratio, belonging to the same geographical area and very probably to the same period of intrusion. Again, the analyses of the Holyrood granite, rhyolite porphyry near Holyrood, and a rhyolite flow from the Avondale volcanics near Manuels, constituting a batholith, a volcanic neck, and a volcanic flow respectively, show but slight variation in composition, although the texture varies widely. The chemical differences between the granite on the one hand, and the rhyolite porphyry and rhyolite on the other, are the usual relative increase in silica and loss of alumina, lime, magnesia, and iron in the volcanic facies. Again, the plutonic gabbros, a volcanic plug of plagioclase basalt near Manuels, and the Blue Hills basalt flows may be cited as textural facies of a similar basic magma. The repeated recurrence and abundance of intrusions of magma of basaltic composition in dikelike form throughout the entire peninsula, in contrast to the restricted local character of the salic intrusions with their associated infrequent dikes, rather

impress one with the idea that a basaltic magma was the one from which the salic differentiates originated.

CONCLUSION

The points brought out in this paper which it is desired to emphasize are as follows:

1. The confirmation of the local glaciation of the Avalon Peninsula, of the control of faults and fractures over the lineaments of the topography, and of the fiord nature of the coast.

2. The description and confirmation of the presence of a thick series of volcanics at the base of the pre-Cambrian section.

3. The presentation of evidence pointing toward the origin of the members of the later pre-Cambrian series, as follows:

a) The Avondale volcanics as subaërial accumulations of volcanic materials derived from volcanoes of the central type.

b) The Conception slate series as materials derived from rocks resembling the Avondale volcanics swept into the sea in a comparatively fresh, unaltered condition.

c) The Momable formation as well-decomposed marine sediments with traces of organic life.

d) The Signal Hill reddish-brown sandstone series as dominantly subaërial fluviatile deposits in a subarid climate, derived from a re-working of volcanic rocks resembling members of the Avondale volcanics.

4. The evidence of a comagmatic series of igneous rocks intruded probably at some time during early or middle Proterozoic time.

5. The entire series from bottom to top is derived directly or indirectly from rocks of volcanic origin.

The author wishes to acknowledge his indebtedness to Professors van Ingen and Smyth for their cordial assistance and advice rendered to him throughout the course of the work, and to Mr. B. F. Howell for his assistance during the summer of 1913.

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CURIOUS EROSION FEATURE IN WEST TENNESSEE CLAYS

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Recently the writer had occasion to observe a rather odd and striking phenomenon. The clay strata of West Tennessee lie in nearly horizontal beds of unconsolidated sands of the Ripley and Lagrange (Wilcox) formations and are very liable to active erosion. During torrential rains, which are common in this region,

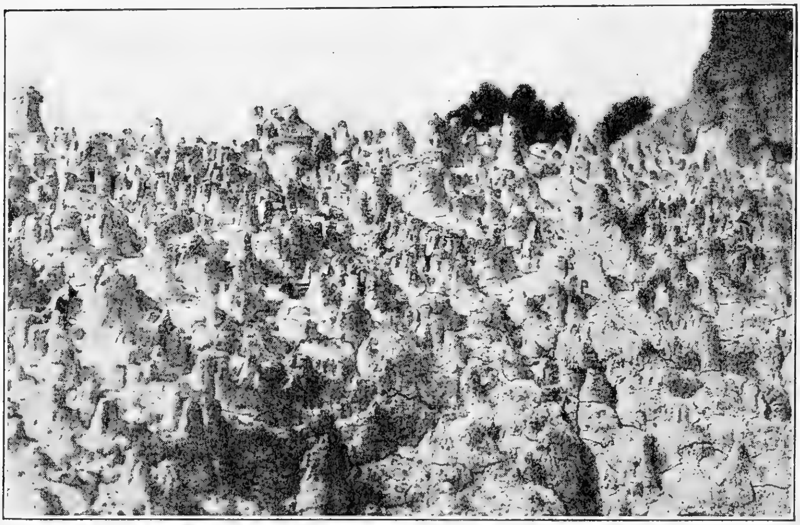

FIG. 1.—Miniature erosion pillars in clay. (Scale, 1 inch = 1 foot.)

small columns are sometimes carved in the surface of the exposed clay. These have been termed "miniature hoodoos" by the writer, for they are in fact small editions of the pillars or "hoodoos" so well known in Monument Park, Colorado, and have the same origin. They are rarely more than six inches high, are circular or elliptical in horizontal section, and generally closely

spaced (15–20 per square foot). Thin fragments of hardpan (ferruginous sandstone) commonly form the protective capping and are derived from the overburden. Other substances, such as leaves, bits of wood, and concretions, function in the same way. In short, any small, flat piece of coherent matter will do. These miniature hoodoos are very abundant in this region and are especially characteristic of very plastic clays.

Reviews

The Principles of Economic Geology. By W. H. Emmons. New York: McGraw-Hill Book Co., Inc. Pp. 606, with 208 figures. 1918.

In *The Principles of Economic Geology* Professor Emmons has aimed to give advanced students of geology a general survey of the science of mineral deposits. The fuels have purposely been omitted, however, as to have treated them adequately would have enlarged the book unduly, and evidently for the same reason the non-metalliferous deposits are somewhat briefly described, receiving but one chapter of the twenty-eight in the book. The volume is thus in essence a condensed treatise on ore deposits; its central concept is that most ore deposits (except an important group of sedimentary origin) are genetically related to igneous rocks.

The first chapter consists almost wholly of definitions, such as ore, protore, etc., a necessary groundwork, but it forms a rather heavy introduction to the subject and is likely to dull the interest of students coming fresh to the subject; fortunately the chapter is but three pages long. A suggestive outline of the objects of economic geology, its problems, and its broader relations to petrology and geology would perhaps make a more attractive introduction. The second chapter takes us deep into the subject, namely, the classification of ore deposits. Primary ore deposits are grouped under eight major heads:

1. Deposits formed by magmatic segregation; consolidated from molten magmas.

2. Pegmatite veins; deposited by aqueo-igneous magmatic solutions.

3. Contact-metamorphic deposits; deposited in intruded rocks by fluids passing from consolidating intruding rocks.

4. Deposits of the deep vein zone; formed at high temperature and under great pressure, generally in and along fissures.

5. Deposits formed at moderate depths by ascending hot solutions.

6. Deposits formed at shallow depths by ascending hot solutions.

7. Deposits formed at moderate and shallow depths by cold meteoric solutions.

8. Sedimentary deposits; chemical, mechanical, organic, etc.

These classes are then briefly characterized, perhaps somewhat too briefly to differentiate them clearly in the student's mind at this stage of his knowledge of the subject. For example, the characterization of contact-metamorphic deposits is insufficient to distinguish them sharply from deposits of classes 4, 5, and 6.

The next eight chapters take up one by one the several classes of the scheme. They are models of clear and concise presentation.

In the chapter on the sedimentary deposits is given an interesting diagram that shows approximately what proportion of the primary ores and protores of each of the various metals occur in the eight groups of the genetic classification.

Chapters 11 to 21 inclusive deal with the more general phases of the subject, such as primary ore shoots, the origin of thermal metalliferous waters, and so on. The chapter on Superficial Alteration and Enrichment is of course particularly good, as is to be expected of a field that the author has so notably made his own. It is somewhat surprising, however, to find that he has made no use of the newer solubility determinations of the metallic sulphides as given in Stieglitz' *Qualitative Analysis* or in Abegg's *Handbuch der Anorganische Chemie;* had he used these, rather than those of Weigel, he would have found less difficulty in reconciling them with the known facts of secondary enrichment.

The second half of the book (chapters 22 to 28, comprising 299 pages) treats of the metals and more important non-metals. The chief valuable minerals of each metal and non-metal are described, chiefly in their economic aspects, the genesis of the deposits is sketched, the age of the deposits occurring in the United States is discussed, and certain specific or distinctive features of the geology of each substance, such as sulphide enrichment in the chapter on copper, are specially considered. Although some economic geologists have objected to this mode of treatment by substances, it is an eminently satisfactory way of giving the subject concreteness to the student. As DeLaunay says, the treatment by types of deposits, in spite of important advantages, has the grave fault of scattering the descriptions of deposits of the same substance according to a system that is necessarily somewhat hypothetical and arbitrary. The general treatment of each metal or non-metal is followed by descriptions of mining districts, practically all of which are chosen from the United States. For some reason not clearly apparent the order in which they are described conforms neither with the genetic classification of the first half of the book nor with the order of their

commercial importance. In the chapter on iron, the Lake Superior deposits receive an undue amount of attention in view of the title of the book, and following what seems to have become a convention among those intrusted to teach geology, a large number of stratigraphic columns built up of many formations and members, doubtless of interest to local geologists, have been introduced, but they add little in elucidating the principles of the science. The reviewer would like to see the chapter on iron recast in accordance with the genetic classification adopted in the book. As illustrating the first category of the classification, the descriptions of the districts might then begin with the igneous iron ores of Kiruna, Sweden, which have been carefully studied by many able geologists and concerning which there is, as a result of the attrition of ideas, a solid nucleus of established fact. It seems desirable that this mode of treatment be extended to the other metals also, and that the representative districts be selected regardless of whether they are or are not in North America. Although the author has purposely chosen the illustrative districts almost wholly from North America, the procedure can hardly be commended, as it encourages provincialism and seems rather a concession to our American linguistic laziness. In the chapter on copper seven of the eighteen districts described are those containing disseminated deposits, which adds much to the amount of information presented, but does not increase the number of principles exemplified. For some of the "porphyry coppers," descriptions of types not now illustrated by the book might profitably be substituted, such as those of Mansfeld, Sulitelma, and Little Namaqualand.

In naming this volume *The Principles of Economic Geology*, Professor Emmons has given it a highly attractive title—one which arouses the expectation that the book thus distinguished will deal in a broad and stimulating way with the firmly established generalizations of the subject. If in places it deviates from the ideal suggested by its title and becomes burdened with details, these departures are after all easily forgotten in view of the general excellence of the book. The subject is accurately, clearly, and succinctly presented, and is well illustrated by numerous carefully chosen text figures. The author has achieved the plan he set himself to accomplish—to give a conspectus of the subject for advanced students of geology—and for this purpose the book is undoubtedly the best text on economic geology that has yet been written.

ADOLPH KNOPF

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VOLUME XXVII NUMBER 7

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

OCTOBER-NOVEMBER 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, LONDON
THE MARUZEN-KABUSHIKI-KAISHA, TOKYO, OSAKA, KYOTO, FUKUOKA, SENDAI
THE MISSION BOOK COMPANY, SHANGHAI

October-November 1919 Vol. XXVII, No. 7

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

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Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

VOLUME XXVII NUMBER 7

THE

JOURNAL OF GEOLOGY

OCTOBER-NOVEMBER 1919

THE LATE PLEISTOCENE SUBMERGENCE IN THE COLUMBIA VALLEY OF OREGON AND WASHINGTON

J HARLEN BRETZ
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This article aims to review previous references to a Champlain submergence in the lower drainage of Columbia River, to eliminate erroneous interpretations and correlate data which belong to this subject, to present more evidence establishing the fact, to define the character and the extent of the submergence, to correlate this with the Pleistocene history of northwestern Washington, and to indicate questions which are still unanswered.

HISTORICAL

So far as known, Thomas Condon published the first note on static water in the Columbia Valley during late Pleistocene time. This was an article entitled "The Willamette Sound" in the *Overland Monthly*, 1871.[1] Condon argued for a submergence of at least 330 feet above present tide, the waters flooding Willamette Valley and backing up through the Gorge of the Columbia across the Cascade Range and submerging portions of the tributary Yakima and Walla Walla valleys. Condon's evidence was the

[1] The article has been reprinted as a chapter in Condon's *The Two Islands* (Portland: J. K. Gill, 1902), and also in his *Oregon Geology* (1910), a revision of *The Two Islands*.

existence of marine Pleistocene deposits along Shoalwater Bay, Washington, 10 to 15 miles north of the mouth of Columbia River, and fossiliferous beds below about 330 feet A.T. at the mouth of Des Chutes River, an Oregon tributary entering the Columbia immediately east of the Cascade Range. If the sediments in these two localities, more than 150 miles distant from each other, were deposited in the same body of water, then Willamette Valley of western Oregon, intermediate in position, must have been largely submerged. To this water body Condon gave the name of Willamette Sound. He correlated it with the Champlain submergence on the Atlantic Coast.

Static waters in the Columbia Valley east of the Cascade Range were postulated by T. W. Symons in a Senate document,[1] published in 1882, dealing chiefly with navigation of the Columbia. Symons saw many rounded bowlders on the basalt plateau along the Columbia in central Washington, he saw considerable tracts of the basalt covered with sedimentary deposits, and he found large, though fragmentary, gravel terraces in the Columbia Valley. All of these he ascribed to a glacial lake which he named Lake Lewis. He thought this lake extended southward as far as Walla Walla and Wallula. He gave no altitudes, cited no evidence for the Champlain age which he assumed for the submergence, and suggested no cause for the ponding.

I. C. Russell made a geological reconnaissance in central Washington in 1892, and in his report[2] revised Symons' data somewhat but adopted his conception of a glacial lake. His revision consisted in eliminating the sedimentary formation exposed in White Bluffs along the Columbia. This he considered to be a portion of the John Day Series of Tertiary age. He also added the valuable item that there were many foreign granite bowlders in the Columbia and Yakima valleys which had been carried in bergs to their present positions. Russell thought that a glacier might have dammed Columbia River at The Dalles, just below the mouth of Des Chutes River, but he admitted the possibility of subsidence

[1] "The Upper Columbia River and the Great Plain of the Columbia," *Senate Document No. 186*, Forty-seventh Congress, 1st sess., Washington, 1882.

[2] "A Geological Reconnaissance in Central Washington," *U.S. Geol. Surv., Bull. 108* (1893).

allowing "the ocean to enter the great central valley between the Cascades and Rocky mountains."

J. S. Diller published his geological reconnaissance of northwestern Oregon[1] two years after the appearance of Russell's report. In it he adopted Condon's notion of a Willamette Sound. Like Russell, he announced the existence of foreign bowlders in the valley and interpreted these as berg-carried in the waters of a Pleistocene submergence.

Russell, in another paper, published in 1898,[2] stated his belief that the Great Terrace in the Columbia Valley, between the junction of the Methow and Chelan valleys, was a delta built in Lake Lewis. He considered that the termination of the Great Terrace, a little below the mouth of Chelan River, was the delta front. Russell noted here that "full and unquestionable evidence of its [the lake's] actual existence cannot be said to have been discovered."

CRITICAL EXAMINATION OF THE DATA PRESENTED BY THE FOREGOING WRITERS

Shoalwater Bay.—These deposits, cited by Condon, are unquestionably part of the coastal phase of the Satsop formation.[3] This formation is largely a river gravel in the Columbia Valley, and only along the coast was it deposited in standing water. In the Shoalwater Bay (Willapa Bay) exposures there is abundant evidence in the presence of gravel strata containing granite, gneiss, and much quartzite that a vigorous current existed throughout the length of the Columbia in Oregon and Washington when these beds were deposited. Though the Satsop is believed from paleontological evidence to be Quaternary in age, it was laid down before the present Cascade Range was folded and therefore long antedates the Champlain epoch. The strata along Shoalwater Bay therefore do not record a Willamette Sound.

[1] "A Geological Reconnaissance in Northwestern Oregon," *U.S. Geol. Surv., 17th Ann. Rept.*, Part I (1895).

[2] "The Great Terrace of the Columbia," *Amer. Geologist*, XXII (1898), 363.

[3] J H. Bretz, "The Satsop Formation of Oregon and Washington," *Jour. Geol.*, XXV (1917), 447.

Des Chutes terrace.—Condon gave no list of fossils from the terrace deposit. He simply said the material was stratified clays, sands, and gravels containing tusks, teeth, and bones "of the land animals of that period, marking at once the height at which these waters stood." No one has since studied the fauna from this locality. There are many Tertiary formations, with vertebrate faunas, in Oregon and Washington in the great lava plain east of the Cascades. The terrace may be the outcropping edge of a formation of this kind, and not a remnant of a post-valley filling. The feature, so far as known, gives no positive evidence for the existence of Willamette Sound.

The Dalles, Oregon.—Condon mentioned sediments deposited in ravines cut in The Dalles beds at this place and ascribed them to Willamette Sound.

Swan Island, Portland.—Quoting Condon: "Currents of such a vast body of water [Willamette Sound] . . . . the agency competent to the heaping up of that long sandy ridge, 100 feet high, through which the river has cut at Swan Island, north of Portland." This ridge is a terrace remnant; left by erosion, not deposition; and is a portion of a great delta of the Columbia built in Willamette Valley. Static waters stood no higher than its surface (300 feet A.T.) when the delta was built. If related to Willamette Sound it is probably a record of the subsiding stages. It will be discussed more fully later in this paper.

White Bluffs (Ringgold formation), Washington.—Merriam and Buwalda recently have shown[1] that the sedimentary formation exposed in White Bluffs is of very late Cenozoic age, probably Pleistocene. They favor the view that it is a flood-plain deposit, and not lacustral. Its summit plane is considerably below the upper limit of drifted erratics, and on this point it cannot be ruled out of the list of phenomena bearing on the Columbia submergence that we are discussing. But it rises 300 feet higher than the broad gravel terraces on the opposite side of the river, and these are very probably deposits of the river immediately following the Champlain submergence. Merriam and Buwalda found no bowlders of any

[1] "Age of Strata Referred to the Ellensburg Formation in the White Bluffs of the Columbia River," *University of California, Dept. Geol. Bull.*, X (1917), 255.

kind in the materials exposed in the 500-foot sections they studied. Absence of anything attributable to floating ice, presence of a fauna of land vertebrates, and the existence of a broad valley cut in the Ringgold formation containing gravel deposited probably during subsiding stages of the submergence seem adequate evidence for ruling the Ringgold formation out of the catalogue of records of Lake Lewis.

"*Sediments north of Saddle Mountains.*"—It is difficult to determine just what Symons meant by this phrase. There are sediments in that region which are warped with the basalt, and there are horizontal sediments, noted as lake beds of Pleistocene age,[1] which lie below the upper limits of this submergence. These are very poorly exposed and best known from well records. There are also fluvioglacial gravels, deposited by the diverted Columbia during subsiding stages of the submergence and correlative with the gravel terraces of the present Columbia Valley.

"*Rounded bowlders and a loose, light, powdery soil.*"—These occur south of Badger Mountain and Crab Creek, surrounding Saddle Mountain, and in the lower portions of the valleys of Yakima River, Walla Walla River, Snake River, and Moses Lake. Symons here grouped a congeries of deposits of varied genesis: fluvial, fluvioglacial, static water, and wind.

Gravel terraces (cited by Symons).—These are fluvial and fluvioglacial deposits and probably only the Great Terrace, above noted, can be correlated with Lake Lewis.

Neither Condon's nor Symons' work was more than hasty reconnaissance. No one then knew that the sediments of many successive Tertiary basins are exposed in the region, and neither observer was carefully discriminative. Neither one noted the existence of *erratics* in the Columbia Valley. Correlation with the Champlain epoch of the eastern states was with both wholly a matter of inference, on the assumption that the Pacific Coast must have been submerged if the Atlantic Coast was.

Russell (1893) was the first to recognize the significance of the erratic bowlders as evidence for the existence and the age of the

[1] A. T. Schwennesen and O. E. Meinzer, "Ground Water in Quincy Valley, Washington," *U.S. Geol. Surv., Water Supply Paper 425-E,* 1918.

ancient water body. He believed that they were derived from the Okanogan Lobe of the Cordilleran ice sheet. He found these stranded erratics from the mouth of Wenatchee Valley to the lower portion of Yakima Valley.

Diller (1895) cited the erratic bowlders of the Willamette Valley as his contribution to the evidences for this Pleistocene submergence. As in Russell's amplification of Symons' idea of a lake, Diller supplied the only trustworthy evidence (and the convincing proof) of the existence of a late Pleistocene water body in the Willamette Valley. Diller, however, thought that the berg-carried bowlders were derived from glaciers descending the western slope of the Cascades. No granite, schist, or quartzite are known to outcrop in this portion of the range, and it is clear that the erratics were carried through the Gorge from regions east of these mountains. If Diller was aware of the publications of Symons and of Russell on Lake Lewis, he did not suggest correlation between this lake and Willamette Sound.

Here, then, is a curious situation with regard to nomenclature. Condon (1871) has priority of publication, but, so far as we can learn, his conclusion cannot stand on his own presented evidence. It is purely a coincidence that there *was* such a submergence as he names. Symons (1882) has a case nearly identical. If Symons had indicated that he found *erratic* or *glaciated* bowlders, his case would have been clear. Russell (1893) did not know of Condon's publication, or he would have mentioned it when he admitted that the cause of the ponding was not known. He preferred the hypothesis of a glacial dam. It seems unlikely that he did not know of Diller's discovery of granite erratics in the Willamette Valley before his own last-published mention of Lake Lewis (1898). Yet he consistently referred to the ponding as Lake Lewis, clearly not correlating the episode in central Washington with that in western Oregon. Russell and Diller independently discovered the evidence which establishes the existence of the water body under discussion. They are to be credited accordingly, though neither saw as broad a vision as did Condon.

There was never a glacial dam across the Columbia in the Gorge. The drifted bowlders in Willamette Valley, derived from

the east side of the range, are clear evidence of open waters through the Gorge at the time of the submergence. Further, a study of the various tributary valleys along the Gorge shows that local glaciers, instead of filling it to a depth of more than a thousand feet, probably never reached the Columbia. In Hood River Valley there are moraine deposits apparently recording two different glaciations, during the earlier of which the ice reached within 3 miles of the Columbia, and during the later not nearer than 5 miles. No other local glacier got as near as this to the Columbia. It seems impossible that Hood River Glacier could have filled the Columbia Valley to a depth exceeding a thousand feet and left no trace other than these minor deposits back in the tributary valley. Both Condon[1] and LeConte[2] have referred to glacial deposits near The Dalles, but the writer has never seen anything in this region which could be so interpreted. Topographic situations, altitudes, and the location on the lee side of a mountain range all contribute to weaken the hypothesis of glaciation at or near The Dalles. The Yakima Glacier, on the east slope of the range, 100 miles farther north, did not descend below 2,000 feet A.T., though it was fed from mountains much loftier than those near The Dalles.

NEW EVIDENCE ESTABLISHING THE FACT AND EXTENT OF THE SUBMERGENCE

Foreign bowlders and dêbris.—This can best take the form of a list of occurrences and altitudes of foreign materials along the Columbia and in some of its tributary valleys.

Kelso, Wash. (5 mi. west of). Granite bowlder, $2\frac{1}{2}$ ft. in maximum diameter. 50 ft. A.T. Has a pegmatite dike in it. Dike projects $\frac{1}{2}$ in. above the pitted surface of the granite.

Manor, Wash. (8 mi. north of Vancouver, Wash.). Granite bowlder in schoolyard; angular, with fresh surface. Altitude close to 300 ft. A.T.

Camas, Wash. Granite bowlder formerly on terrace back of the town, at an altitude of about 175 ft. A.T. Has been broken up and used for foundations. A fragment of it was examined.

Willamette, Ore. (4 mi. southwest of). Several granite and quartzite bowlders lying at the western foot of Pete's Mountain at 300 ft. A.T. Very slightly weathered.

[1] Thomas Condon, *The Two Islands* (Portland, 1902).

[2] Joseph LeConte, "Age of the Cascade Mountains," *Amer. Jour. Sci.*, VII (1874), 167.

Canby, Ore. (4 mi. east of). Several erratic bowlders; granite or granodiorite, porphyritic rhyolite, and quartzite. Altitude 323 ft. A.T. Have been blasted out of the soil in clearing a field. Local authority states that a granite bowlder like those in this group lies on the plateau tract 4 to 5 mi. north of Canby. Its altitude must be about 450 ft. A.T.

Dilley, Amity, and Corvallis, Ore. Diller found foreign bowlders near these places in the Willamette Valley, the highest at 250 ft. A.T. He quotes local authority for their occurrence as high as 1,500 ft. A.T. "near" Oswego, Ore., but there are no elevations of more than 950 ft. A.T. near enough to this place to be referred to its locality.

Granite bowlders are very rare in the Gorge, east of the Willamette broadening. Only one has ever been seen by the writer and none are noted in the literature. The lone bowlder lies in Hood River Valley, Oregon, on the summit of Van Horn Butte, a small cinder cone three-quarters of a mile southeast of Van Horn. It is of granite. Its altitude is between 800 and 900 feet A.T. Immediately east of the Gorge, however, the foreign bowlders are more common than in the Willamette Valley. They occur on the eastern flank of the easternmost anticline of the Cascade Range, about the city of The Dalles, Oregon.

The Dalles, Ore. Granite bowlder on summit of terrace immediately south of the city reservoir.

The Dalles. Valley of Mill Creek, $1\frac{1}{2}$ mi. from town. Large granite bowlder lies in the valley; probably has fallen from the summit of the bluffs, about 500 ft. A.T.

The Dalles (about 6 mi. west of), on old Hood River road. A dozen or more angular fragments of granite, 2–3 ft. in maximum diameter, grouped as though the result of frost action or blasting of an original large bowlder. Altitude about 1,200 ft. A.T.

The Dalles (about 6 mi. west of), north of old Hood River road. Granite bowlder, maximum diameter about 3 ft. 500 ft. A.T.

Arlington, Ore. (1 mi. east of). 30 to 40 angular pieces of granite, from 2 to 6 ft. in maximum diameter, grouped within a radius of 25 ft. Altitude 800 ft.+ A.T. Estimated volume of exposed granite material, 500 cu. ft., equivalent to an original bowlder about $7\times 7\times 8$. The granite is light gray in color, composed of quartz, feldspar, mica, and hornblende, and contains lenses and fragments of a dark ferromagnesian phanerite. Portions are a true intrusion breccia. Many of these huge granite bowlders are said to lie on the slopes south of Arlington. Many of them have been broken up for use in cemetery monuments.

Roosevelt, Wash. Slates, diorites, quartzites, and several varieties of granite are all represented in cobbly and bowldery fragments up to 1,000 ft.

A.T. on the slopes of Wood Gulch back of this town. One quartzite, 8 in. in diameter, has glacial striae on one side. These fragments lie below the outcrop of an intra-basalt gravel formation, but quite surely are not derived from it.

Mottinger, Wash. (4 mi. north of). A distinct mound 4 ft. high and 40 ft. in diameter, covered with, and apparently composed of, glacial débris of various kinds, the fragments of various sizes and shapes. It is literally a patch of glacial till deposited on this unglaciated slope. Altitude about 1,100 ft. A.T.

FIG. 1.—Erratic near Prosser, Wash.

Kennewick, Wash. ($3\frac{1}{2}$ mi. south of). Foreign material very abundant on slopes and summit of the ridge. Summit is 900 ft. A.T. Granite, gneiss, quartzite, vein quartz, slate, porphyritic phanerites and a variety of metamorphic rock fragments are present. Striated faces are common. In places here the soil looks like the washed surface of a stony glacial till, though the region is many miles from the nearest glaciated area.

Prosser, Wash. (north of). Slopes below about 1,000 ft. bear many bowlders and fragments of granite and quartzite. The quartzite is prevailingly pinkish to lavender to blue in color, a feature common to most of the angular quartzite in this category. One quartzite is marked with two sets of striae crossing each other. One large granite bowlder, $6\times7\times10$, lies at 840 ft. A.T. along the road. It is almost identical in character with the material at Arlington. Riven fragments lying about the bowlder are equal in volume to half the main bowlder (Fig. 1).

Mabton, Wash. (southwest of). Foreign bowlders and cobbles of granite, quartzite, slate, and basalt in considerable numbers lie scattered over the

surface of the fine, light-colored silt which floors this part of the Yakima Valley. Upper limit 1,200 ft. A.T. These erratics occur in groups, several kinds of rock in each group. Both rounded and angular, and both large and small fragments occur in every group.

Snipes Mountain, Wash., between Granger and Sunnyside. Foreign cobbles and bowlders common, scattered over the hillside up to nearly 1,200 ft. A.T. One granite, $2\times3\times4$, at 950 ft. A.T., has a flat, beautifully striated face, 3×4 ft., undoubtedly a glaciated surface.

Toppenish Ridge and Satus Valley, Wash., 5 to 8 mi. south of Toppenish. A striated quartzite bowlder, associated with granite and other foreign material, at about 1,100 ft. A.T. A granite bowlder at 1,100 ft. on the south side of the Satus Valley.

Ahtanum Ridge, Wash. (10 mi. S.S.W. of Yakima). Large numbers of angular granite and quartzite bowlders and cobbles on the southern slopes, below 1,200 ft., and on the floor of the structural valley immediately south. Grouping of angular fragments indicate that some original bowlders were 4 to 5 ft. in diameter. Material fresh, affected only by frost action and temperature changes. One bowlder along road, about midway between Yakima and White Swan, is clearly smoothed and striated on one face.[1]

Dry Creek Valley, Wash. Glacial material plentiful; granite predominant, but quartzite, diorite, slate, etc., present. Observed upper limit about 1,100 ft. A.T. Grouped in the familiar fashion: large and small, rounded and angular, all together except where slope wash has strung them out. Groups separated by intervals of hundreds or thousands of feet where no débris of this sort is to be found. Glaciated surfaces on some bowlders.

Cold Creek Valley, Wash. Situation similar to that in Dry Creek Valley 1,130 ft. maximum altitude observed.

Priest Rapids, Wash. (4 mi. northwest of). Granite bowlders lie on the slopes of the Columbia Valley up to 1,175 ft. A.T. The highest found is $3\times4\times6$ exposed, probably larger. Several nearly as large at 1,150 ft. A.T. on the same hill. Granite is like that in the Arlington bowlder.

Quincy and Burke, Wash. Between these two places 10 or 12 foreign bowlders were seen at altitudes above 1,200 ft. Two are described as follows: (1) six mi. south of Quincy; granite bowlder, $4\times5\times10$ exposed dimensions, of the familiar basic igneous rock in a light-colored granite. (2) five mi. south of Quincy; granite bowlder, largely buried, exposed portion 12 ft. long; the largest and the highest (1,255 ft. A.T.) found by the writer.

Wenatchee Valley at junction with Columbia Valley. Russell reports "great quantities of angular bowlders, some of them of large size, composed principally of quartzite, granite and schists . . . . about Wenatchee and

[1] George Otis Smith, in *Ellensburg Folio No. 86, U.S. Geol. Surv.* (1903), notes the presence of erratic bowlders in Wide Hollow and Wenas Valley, north of Ahtanum Ridge, and says they "must have been dropped from masses of ice floating in the ponded waters of Yakima Valley."

along the river to the south . . . . which were carried to their present positions by ice."[1] He does not say "floating ice" but his own later work showed that no glacial ice ever reached this place, and these bowlders may be listed with the others floated in the Columbia submergence.

Soap Lake and Adrian, Wash. Erratic bowlders very abundant along the Great Northern Railroad in vicinity of these stations. The railroad here crosses the old Grand Coulee channel of the Columbia, occupied while the Okanogan lobe blocked the main valley to the west. Altitude of Soap Lake station is 1,202 ft., of Adrian, 1,234 ft. Whether these bowlders were deposited from bergs in Lake Lewis or were dropped while en route to the lake along the glacial Columbia was not determined. At any rate, they lie close to the entrance of the river into the lake. The Coulee City terminal moraine is distant 20 to 25 mi. by the Grand Coulee route, 15 to 20 mi. in a straight line, and the agency of glacial ice cannot be called upon to explain their presence here.

Ephrata, Wash. "3.7 mi. south of Ephrata, aluminum tablet in large granite bowlder, 1,283.102." Leveled in 1903, by R. A. Farmer and in 1909 by C. H. Semner, of the United States Geological Survey (note taken from *Bull. 674, U.S. Geol. Surv.*)." This is the highest foreign bowlder ever reported from the bed of Lake Lewis, so far as the writer is aware.

Winchester, Wash. "Twenty feet south of track, opposite section house, in top of granite bowlder, aluminum tablet stamped 1277 T. 1277.333" (data from *Bull. 674, U.S. Geol. Surv.*).

The berg-drifted bowlders in the lower Columbia drainage extend almost, if not quite, from the margin of the Okanogan glacial lobe in central Washington to within fifty miles of the Pacific Ocean. This débris did not come from glaciers on the west side of the Cascade Range, for there are no granite outcrops in the drainage of the Willamette Valley. It did not come from glaciers along the east slope of the same range south of Lake Chelan, for none of the valley glaciers here descended below 1,500 feet A.T. and the submergence did not reach much above 1,250 feet A.T. The Chelan Glacier and the Okanogan Lobe appear to have contributed all the bergs which drifted so widely in this inland sea, and débris which they carried was scattered along 350 miles of the lower Columbia Valley.

Most of this débris lies close to the upper limits of the submergence. This is due to two causes: (1) the opportunity for stranding in shallow water along the shores, where the bergs were

[1] "A Geological Reconnaissance in Central Washington," *U.S. Geol. Surv., Bull. 108* (1893).

held until melting, and (2) the subsequent removal or burial of débris dropped in mid-valleys.

Many of the bergs were derived from basal ice in the parent glacier. The amount of fine material associated with the bowlders, and the striated faces of many bowlders, makes this clear.

Practically all of the débris listed in the foregoing catalogue has been derived from rocks of deep-seated origin, indicating the work of glaciers in the heart of an eroded mountain mass.

The upper limit of the submergence, determined from present data on drifted bowlders, is about 1,200 feet through central Washington. The lower altitudes of the known erratics in Willamette Valley may be because the heavy forest above the cleared bottom land conceals higher bowlders. It may also be due to warping in postglacial time along a hinge line approximately coincident with the axis of the Cascade Range.

Off-shore sediments of the submergence.—It is significant that in the lower valley of Yakima River, Dry Creek, and Cold Creek, considerable silt depoists occur below the upper limits of the erratics. Many square miles are covered by these sediments west of Mabton and south of the Yakima flood plain. Here they are dissected to a subdued badland topography and the erratics are scattered widely over the area: on divides, slopes, and valley bottoms. But the material is incoherent and fails to stand in bluffs, so that one cannot be sure that erratics are *inclosed* in the silt deposit. It is probable, however, that these deposits are correlative with those in White Bluffs, now named the Ringgold formation, and older than the glacial submergence.

It is more significant that investigations on water resources in Quincy Valley[1] have shown the presence of "Pleistocene lake beds" below 1,200 feet A.T. Wells nearly 300 feet deep do not penetrate through these beds on Morrison Flat, a few miles west of Moses Lake. These sediments consist of clay, silt, and sand, with a few beds of gravel, and contain bones and shells. "W. H. Dall states that the fossils collected from the lake beds are fresh-water species, all of which are still living and are not older than the Quaternary period.. They are of the boreal type and could have lived in the cold water of a glacial lake."[2] Glacial gravels unconformably

[1] Schwennesen and Meinzer, *op. cit.*

[2] *Ibid.*, p. 144.

overlie the lake beds, the gravels having been carried down Grand Coulee from the Okanogan Lobe during the subsiding stages of the submergence.

The situation of these deposits near the ice and at the northern extremity of the submergence, and the presence of intercalated gravelly strata make a strong case for their origin in Lake Lewis. If the interbedded gravels were known to contain material of glacial derivation, the case would be clear. Schwennesen and Meinzer think that this lake was local, and that it discharged to the present valley of the Columbia over two abandoned cataracts south and a little west of Quincy. They apparently do not accept the hypothesis of a Lake Lewis as enlarged and set forth by Russell.

Gravel terraces in the Columbia Valley.—Russell and others have noted the presence of several terraces of gravel at different levels in the Columbia Valley from Chelan upstream. The Great Terrace, as Russell called it, appears to be the highest gravel bench in this part of the Columbia Valley. Its altitude near the downstream termination is 600 to 700 feet above the Columbia according to Russell. The Columbia at the mouth of Chelan River is 670 feet A.T., and the surface of the terrace therefore is 1,270 to 1,370 feet A.T. If the Great Terrace is a delta built in Lake Lewis, as Russell thought, and if the present termination is the original delta front, the submergence stood between 1,270 and 1,370 feet in this part of Washington.

The high line of drifted débris is not known to reach above 1,283 feet A.T., though of course the highest bowlders may not have been found. At any rate the close approximation in altitudes strengthens Russell's case for the delta origin in Lake Lewis of the Great Terrace. If top-set beds on fore-set beds are ever found in this terrace their presence will settle the matter affirmatively, and the altitude of their contact will give the precise upper limit of the submergence in this part of the state. If Russell were correct about this, there should also be deltas correlative with the Great Terrace in such tributary valleys as carried glacially fed, and therefore actively aggrading, streams at this time.

The Columbia Valley contains gravel terraces at intervals from the Great Terrace to Portland. Too little is known of these to attempt their interpretation here, but the upper limit of each

highest terrace of the localities known is lower with distance downstream. Apparently they form a simple system of river terraces. So far as known their surfaces do not bear the drifted erratics. They are believed to have been formed during and after the subsiding stages of the submergence. One set of these terraces, here named the Portland Delta, is described as follows:

The eastern portion of the city of Portland is built on a series of terraces of river gravel, the highest of which is about 300 feet A.T. The 300-foot portions lie east of Mount Tabor and Rocky Butte and extend eastward up the river to the mouth of the Gorge. Considerable tracts at 300 feet A.T. also lie on the Washington side of the Columbia, east of Vancouver. This 300-foot plain has been dissected by subsequent meanderings and braidings of the Columbia, and a large portion of it has been brought down to about 200 feet A.T. One of these abandoned Columbia channels is traceable from Rocky Butte in the northeast part of Portland westward to the Willamette in the heart of the city. Another is conspicuous immediately east of Vancouver, Washington, across to the 300-foot plain.

The gravel composing the 300-foot plain and 200-foot terraces is fresh material, discolored only slightly by weathering at the surface, and all of its constituent pebbles are hard. This criterion distinguishes it from terraces of the much older Satsop formation on the Washington side, the altitudes of the lower of which are by coincidence almost the same as the highest of this series.

The gravel is almost everywhere disposed in fore-set beds which dip westward and northwestward. Any gravel pit in Portland shows this, and the long cut of the Oregon-Washington Railroad and Navigation Company in the eastern part of Portland shows it most strikingly.

This deposit of fresh, delta-bedded gravel, with summit level of 275–300 feet A.T., does not extend down the Columbia farther than 10 miles north of Vancouver, Washington. Its outline is that of a broad fan or Greek Δ in the Willamette structural valley, with its apex at the mouth of the gorge. It appears clearly to record static water at this level in the Columbia Valley west of the Cascade Mountains. The absence, so far as known, of the drifted bowlders on its surface, the absence of infiltrated clay in it, and the evidence

from the distributary channels across it of a lowering water body during its formation all suggest that it was deposited after the maximum of the Pleistocene submergence. This may have been either during a pause in the subsidence of the water, or in a later and lesser submergence. The first interpretation is preferred.

THE SUBMERGENCE ELSEWHERE IN WESTERN WASHINGTON

So great a submergence in late Pleistocene time could not have been limited to the lower Columbia drainage. Its duration was so brief, however, that it is not definitely recorded by shore features or lacustrine plains, and had there been no bergs on it the occurrence perhaps and the extent certainly never would have been known.

There appears scant hope, therefore, of finding records of the submergence elsewhere. The only other region in the Pacific Northwest where a similar episode has been reported is the lowland of Puget Sound. During the latest, or Vashon, glaciation of Puget Sound the sea-level was not more than 75 feet above its present altitude.[1] But after retreat of the ice from the lowland, marine waters submerged the northern part of the region to a depth of at least 290 feet A.T.[2] This is recorded by the presence of marine shells in stratified clay overlying the Vashon till sheet.

Erratic bowlders cannot be used for this study in the Puget Sound Valley or its margining slopes because glacial ice has covered the whole region. South of the terminal moraine of the Puget Sound Glacier, however, they would be as valuable a criterion as in the Columbia Valley. But, so far as known, there are no such bowlders in the unglaciated lowlands of southwestern Washington. This may be charged to lack of intensive search for them, or to absence of bergs in such waters.

GENERAL CONSIDERATIONS

The highest known erratic bowlders in Willamette Valley (323 feet A.T.) and the highest known marine shells in Puget Sound (290 feet A.T.) mark the known upper limit of the submergence

[1] J H. Bretz, "Glaciation of the Puget Sound Region," *Wash. Geol. Surv. Bull. 8* (1913), p. 229.

[2] *Ibid.*, p. 233.

west of the Cascades. The hypothesis that submergence was relatively less on this side of the range may therefore be entertained.

Contemporaneity of submergence and glaciation is clearly recorded east of the mountains. In contrast to this it seems clear that in Puget Sound maximum submergence lagged much behind maximum glaciation, highest water-levels not being reached until the ice front had retreated at least 70 miles and probably more than 100 miles.

Though the tides are felt during lower river stages 150 miles up the Columbia, yet Astoria, a few miles inside the Columbia bar, has a fresh-water harbor. The great volume of the Columbia, then as now, doubtless maintained the fresh-water character of the entire submergence. The downstream journey of hundreds of miles by bergs also indicates a current sufficient to offset the influence of the prevailing westerly winds on these bergs. This fresh-water character of the Columbia submergence explains the absence of marine shells in Willamette Valley such as those deposited in Puget Sound during the same epoch.

From the positive evidence of stranded bowlders the submergence reached a known maximum of 1,283 feet A.T. close to the Okanogan Lobe. Its known maximum at The Dalles was 1,200 feet A.T. The Dalles is 125 miles south of the Okanogan Lobe. On the west side of the Cascades the highest records of the submergence in Puget Sound are 290 feet A.T., and bowlders at 250 feet are reported near Corvallis, Oregon, 160 miles south of the front of the Puget Sound Lobe.

Thus there is no evidence in Oregon and Washington for warping along lines parallel to the general front of the Cordilleran ice sheet, nor in central Washington, for progressive submergence of the glaciated area during retreat of the ice. In fact the entire submergence, save in Puget Sound Valley, was confined to territory beyond the limits of glaciation.

Isostatic depression 125 to 150 miles beyond the extremity of the two most extended lobes, and this without detectible warping, seems an impossibility. Furthermore, the apparent warping along a north-south hinge line in the Cascade Range is wholly out of harmony with isostatic adjustment during deglaciation. The submergence, therefore, is referred to diastrophic movements of greater

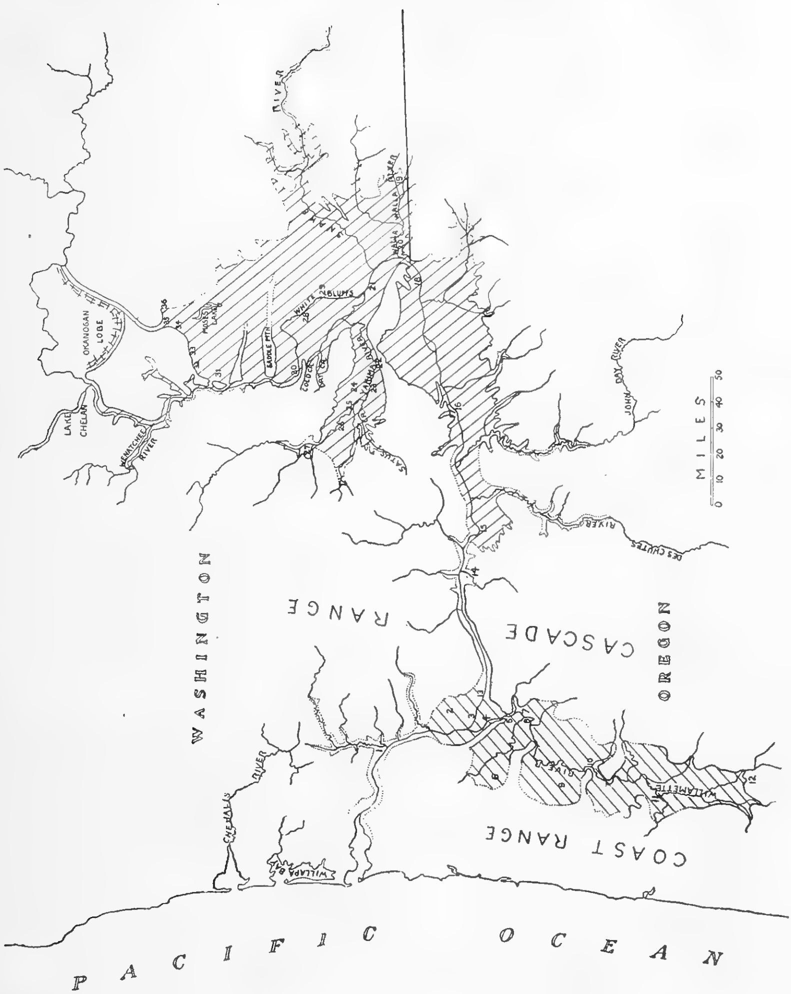

FIG. 2.—The late Pleistocene Columbia submergence

Upper limits of the submergence as shown on this map are 1,250 feet A.T. east of the Cascade Range, 900 feet A.T. in the Columbia Gorge through this range, and 400 feet A.T. west of the range.

N.W.–S.E. diagonal ruling indicates area of Lake Lewis.
N.E.–S.W. diagonal ruling indicates area of Willamette Sound.

1 Kelso, Wash.
2 Manor, Wash.
3 Vancouver, Wash.
4 Portland, Ore.
5 Oswego, Ore.
6 Dilley, Ore.
7 Canby, Ore.
8 Willamette, Ore.
9 Amity, Ore.
10 Salem, Ore.
11 Corvallis, Ore.
12 Eugene, Ore.
13 Camas, Wash.
14 Van Horn, Ore.
15 The Dalles, Ore.
16 Arlington, Ore.
17 Roosevelt, Wash.
18 Mottinger, Wash.
19 Walla Walla, Wash.
20 Wallula, Wash.
21 Kennewick, Wash.
22 Prosser, Wash.
23 Mabton, Wash.
24 Sunnyside, Wash.
25 Granger, Wash.
26 Toppenish, Wash.
27 Yakima, Wash.
28 Hanford, Wash.
29 Ringgold, Wash.
30 Priest Rapids, Wash.
31 Burke, Wash.
32 Quincy, Wash.
33 Winchester, Wash.
34 Ephrata, Wash.
35 Soap Lake, Wash.
36 Adrian, Wash.

extent than, and different genesis from, those resulting from the weight of an ice sheet. In this respect it differs notably from the Champlain submergence of northeastern America.

This hypothesis of a hinge line along the Cascade axis can be most satisfactorily framed in terms of lesser re-elevation west of the range, after the submergence. It is strengthened by the existence of the drowned and alluvium-filled stream valleys of Puget Sound,[1] of the Columbia west of Portland, and of the smaller Chehalis and Willapa valleys. The Columbia east of the Cascades is on a rock floor in many places as far downstream as The Dalles, Oregon.

On the map of the Columbia submergence (Fig. 2) Willamette Sound is assumed to have reached a maximum height of 400 feet. Enough of the valley has been topographically mapped to show that in such a submergence a narrow strait must have existed just south of Portland, and probably another at Salem. Through these straits all the Willamette Valley drainage moved northward.

Diller reports foreign bowlders about Corvallis, south of both straits. It seems impossible that bergs in the Columbia Valley—could have been drifted southward through both straits against the northward flow which must have existed in them. This situation is very strongly suggestive of a submergence in the Willamette Valley even greater than that shown in Figure 2.

When one plots the approximate extent of this submergence in the Columbia Valley on a map, he finds that there were two broadened portions, one on each side of the Cascade Range, connected by a narrow strait in the gorge, and the whole joined to the Pacific by another strait across the Coast Range. If we were dealing with an existing water body of such outline and magnitude we would almost surely find different names applied to such portions. It is therefore proposed to redefine the names "Willamette Sound" and "Lake Lewis," as outlined in this paper, and to continue their use; to recognize the existence of two elongated straits, one across the Cascade Range, the other across the Coast Range; and to consider the whole as "The Columbia Submergence" of the Champlain epoch.

[1] J H. Bretz, "Glaciation of the Puget Sound Region," *Wash. Geol. Surv. Bull. 8* (1913), chap. viii.

A LABORATORY AND FIELD STUDY OF COBBLE ABRASION

Preliminary Report

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University of Chicago

INTRODUCTION AND OBJECT

In the course of field work at Baraboo, Wisconsin, in the summer of 1916, it occurred to me that by means of a suitably designed tumbling barrel an experimental study might be made of the abrasion of cobbles in stream transit. It was believed that by carefully controlling conditions, quantitative determination of change of shape and size as related to distance of travel could be made which, when later combined with field studies, would serve as a valuable criterion in the study of deposits of transported materials. Later in in the summer of 1917, during occasional examinations of gravel deposits, the idea was so cordially received by Mr. A. J. Collier, of the U.S. Geological Survey, that I undertook the study of cobble abrasion at the University of Chicago the following autumn and have continued it, with some interruptions, to the spring of 1919. The following is a brief statement of the principal phases of the problem, the methods used, the more significant results obtained to date, and the points which I hope to take up in the future. More complete description of the methods and more thorough discussion of various conditions and their significance will be reserved for a later paper.

OUTLINE OF STUDY

Aside from lithologic character, the distinguishing features of any cobble are its size, shape, and surface texture. These are subject to change and the change is frequently characteristic of the transporting agent.

In stream transportation the rate of change in size of a given piece depends on: (1) its own size; (2) the size of associated cobbles;

(3) the number of such associated cobbles; (4) its angularity; (5) the violence of the motion; (6) the kind of rock (this factor might be subdivided into *elasticity*, *hardness*, etc.). The change of shape depends on: (7) distance traveled; (8) kind of rock; (9) violence of motion; (10) kind of motion; (11) size of cobble; (12) size of associated cobbles. The change of surface texture depends on: (13) kind of rock; (14) violence of motion; (15) kind of motion; (16) size of cobble; (17) size of associated cobbles.

APPARATUS

The apparatus employed consists of two metal drums lined with soft wood, 25 inches in internal diameter and 13 inches long. These

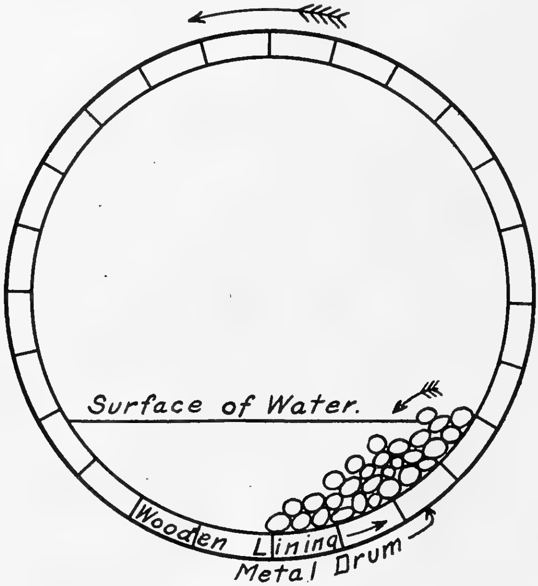

Fig. 1.—Diagram showing in cross-section relations of cobbles to water and to lining of drum while in motion.

are situated at the two ends of the supporting axis and, for all the work to date, have been driven at 27 revolutions per minute. The drums are kept flushed with water so that the finer detritus up to the size of coarse sand is carried out and collects in the settling tubs.

The cobbles in the drums roll continuously down the upgoing side of the barrel, practically under water, at its rate of peripheral travel (1.84 miles per hour or 44.16 miles per day).

The question of how closely the rolling of cobbles down this incline simulates the actual travel of similar materials in streams

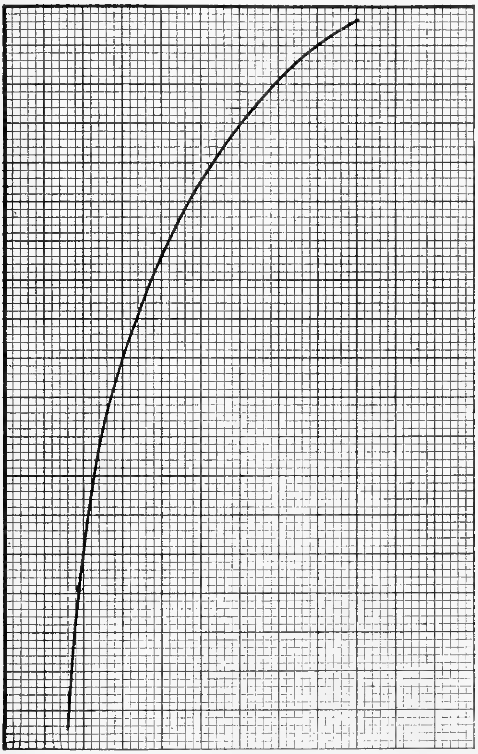

FIG. 2.—Relation of rate of wear to size of cobble

has not yet been carefully investigated. The chief difference, however, will be a constant difference in rate of wear, i.e., 1 mile in a drum equals more or less than 1 mile in the stream, and will not detract from its value in making comparative studies.

It is planned later to make experimental studies of wear during actual transit in streams under natural conditions and

thus determine a factor of comparison to render applicable to field interpretation the comparative results obtained in the laboratory.

I hope also to experiment at length with different speeds and different kinds of motion both in the laboratory and in the field in the hope of throwing some light on the various shapes of cobbles

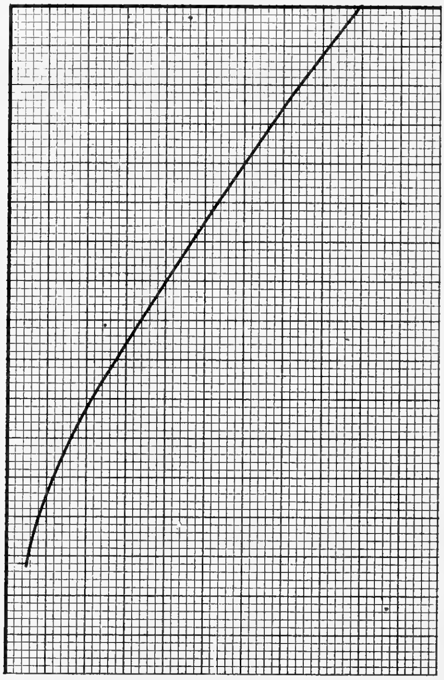

FIG. 3.—Relation of size to distance traveled. Ideal history of cobble starting at 178 grams weight.

thought by some to be characteristic of river deposits, shore deposits, etc. The following are data on some of the relations mentioned above.

RESULTS OBTAINED AND FUTURE WORK PLANNED

1. *Relation of rate of wear to size of cobble.*—I have taken the rate as $\frac{W-W'}{WD}$ where W = initial weight, W' = weight after test, and D = distance of travel, i.e., percentage loss per mile of travel.

Figure 2 shows the plotted average of 85 measurements of rate with cobbles ranging from less than 4 grams to 185 grams. The graph shows very plainly how much more severe the wear becomes as any given piece becomes smaller. This is probably in part due to the increasing ratio of surface to weight.

Figure 3 shows the size history of a cobble started at 180 grams. The rock used in this and all other determinations, unless

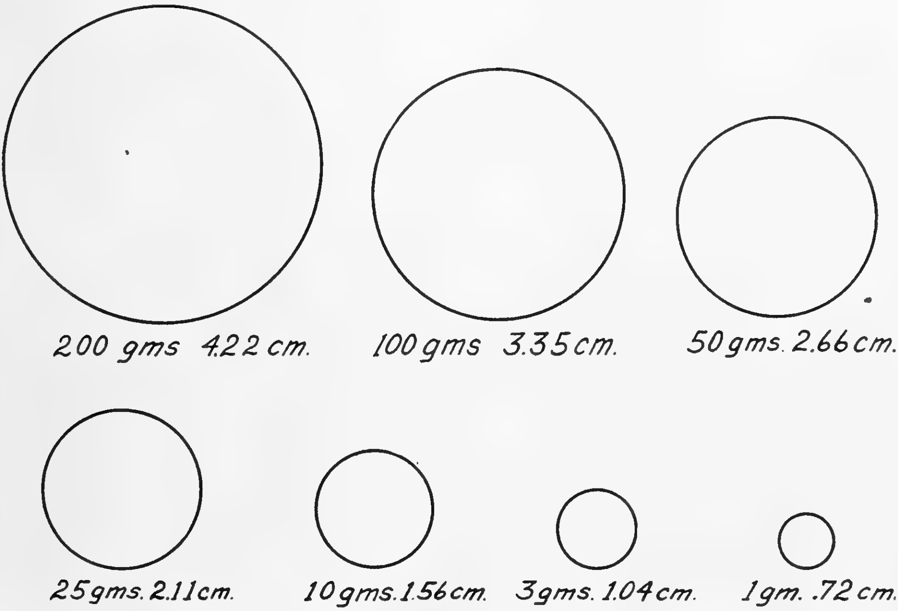

FIG. 4.—Showing sizes of spheres of limestone (density 2.65) of different weights. Weights in grams and diameters in centimeters.

otherwise noted, was Niagara limestone from the outwash gravel at Cary, Illinois. It will be noted that 700 miles of travel reduced the cobbles from 180 to about 10 grams. To aid in visualizing these sizes, Figure 4 may be consulted.

No extensive comparisons have yet been made between different kinds of rock, but measurements were made on one granite cobble which was more than ten times as resistant as the Niagara limestone, and some limestone has been used which was less than one-tenth as durable, so that there is known to be more than one hundred fold

variation in rocks of different sorts. The curve of size history would therefore be notably different in the scale along the abscissa, though the form would be similar for different rocks.

2. *Relation of wear to size of associated cobbles.*—Not yet studied.

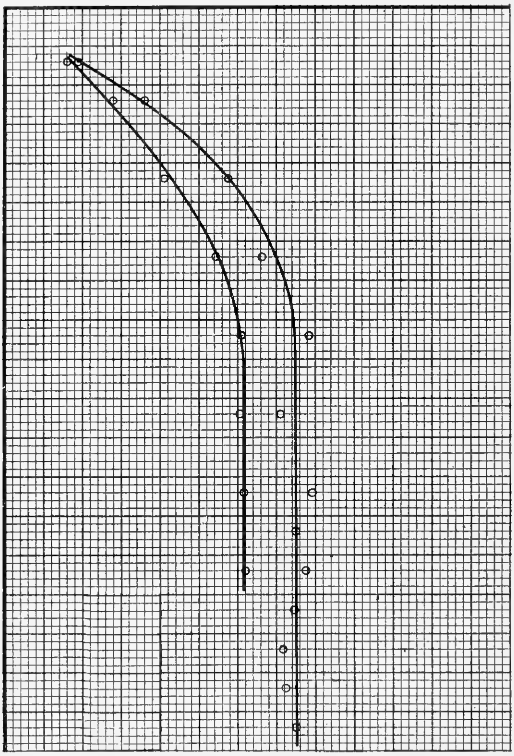

FIG. 5.—Effect of amount of mixture in compartment of drum

3. *Relation of wear to number of associated cobbles.*—That the total amount of material in a compartment of the drum was a very critical factor in the rate of wear was recognized from the first, and to aid in interpreting and correcting for unavoidable variations in the amount, series of runs were made with varying numbers of cobbles in the drum and measurements made on a number of test pieces. The results are shown in Figure 5.

It is to be noted that severity of wear is nearly proportional to the number of cobbles up to a certain point and then remains at an almost constant value. This point, beyond which further additions make little change in rate, is reached when the cobbles are rolling close-packed across the full width of the drum and additional cobbles roll down on top, forming a second layer. Future work will advantageously be done with a filling equal to or greater than 100×41.7 grams to eliminate to a large extent the critical effect of small changes in amount of mixture. The run shown in Figure 5 was started at 144 cobbles, reduced by stages to 14 cobbles, and then increased in an attempt to duplicate the curve. The form is nicely duplicated, while the change in absolute value is due to the diminution in the meantime of the test pieces and their consequent higher rate (see Figure 2); therefore the greater ordinates of the upper and later curve.

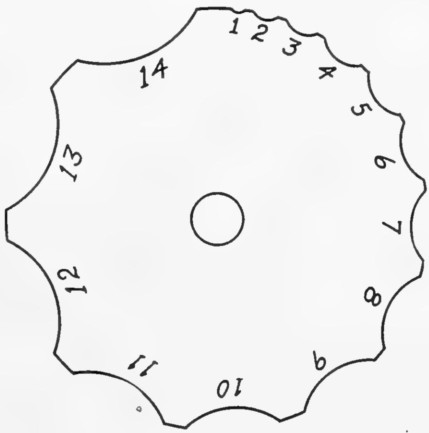

FIG. 6.—Gauge used in measuring curvature. Figures give radii in millimeters.

4. *Relation of wear to angularity.*—Not yet studied.

5. *Relation of wear to violence of motion.*—Not yet studied.

6. *Relation of wear to kind of rock.*—Not yet studied.

7. *Relation of change of shape to distance traveled.*—In stream-transported materials the change in shape, provided the rock is homogeneous, is an approach to sphericity. In studying this change in shape it is necessary to recognize varying degrees of roundness, in other words, to have a numerical answer to the question of how round a given piece is. At least three criteria of roundness readily occur to one in considering the question. These are (1) the ratio of surface area to volume, (2) the average deviation of diameters from a mean diameter, (3) the average

deviation of convexities from a mean convexity. Each of these values or coefficients of roundness reaches a minimum in the case of a sphere and has a maximum in the case of a line or a plane without volume.

Considerable computing and some experimenting was done to test out these methods for the definition of roundness. None was found entirely satisfactory, especially for field use. In order to

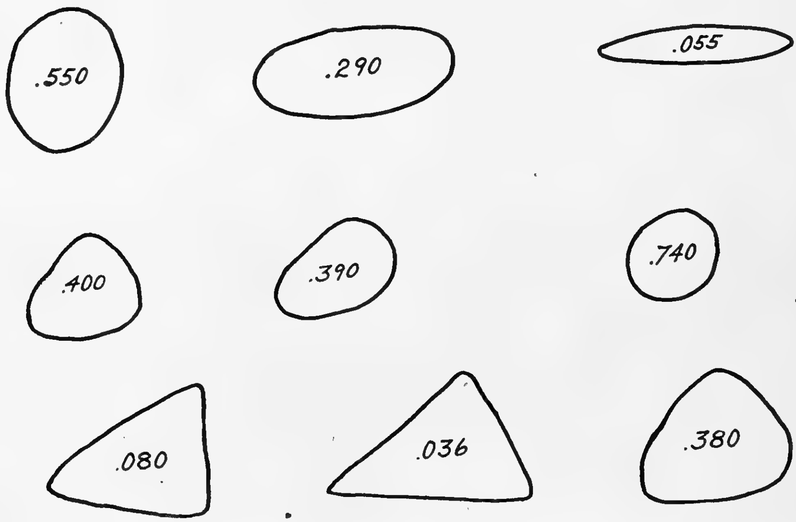

FIG. 7.—Profiles of cobbles showing differing degrees of roundness and giving values of *R*.

be of use in the field study of a deposit, the method of measurement should be simple and rapid enough to permit the calibration of one or two hundred cobbles in a day's time and to allow using the average of the results to characterize the deposit. In (1) the measurement of surface area with sufficient accuracy, while not impossible, was too laborious to use with more than one or two specimens. Likewise in (2) and (3) the need for many measurements of diameters and convexities rendered them liable to the same objection. The method of plotting different kinds of diameters used in the study of cube rounding reported below is of no value for various general shapes. As a practical solution of the

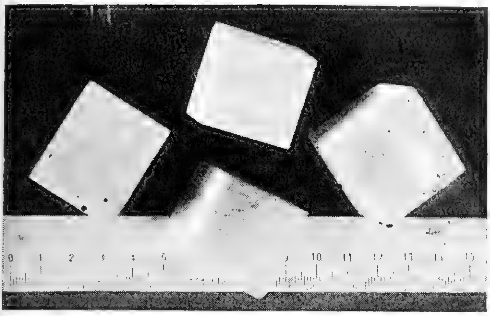

FIG. 8.—Stage 1, 0 miles, $R=0$

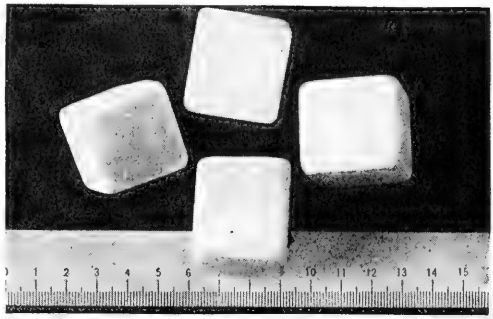

FIG. 11.—Stage 4, 2.18 miles, $R=.130$

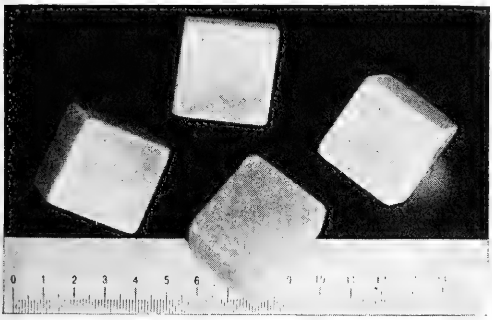

FIG. 9.—Stage 2, .31 miles, $R=.053$

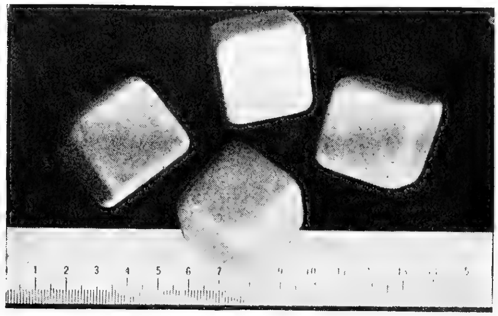

FIG. 12.—Stage 5, 5.12 miles, $R=.170$

FIG. 10.—Stage 3, .91 miles, $R=.096$

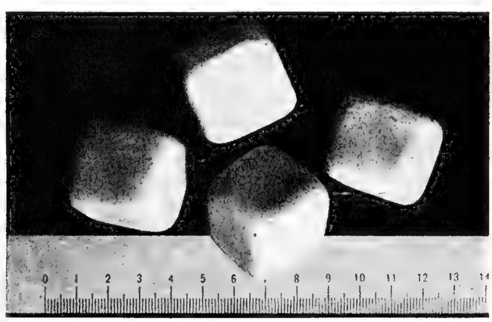

FIG. 13.—Stage 6, 14.1 miles, $R=.250$

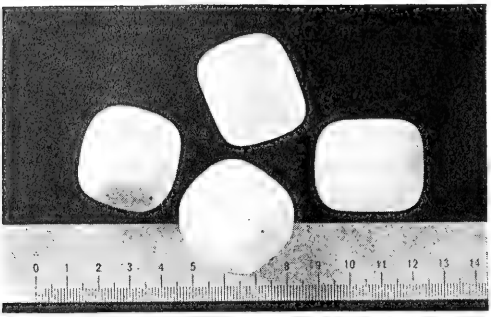

FIG. 14.—Stage 7, 31.5 miles, $R = .400$

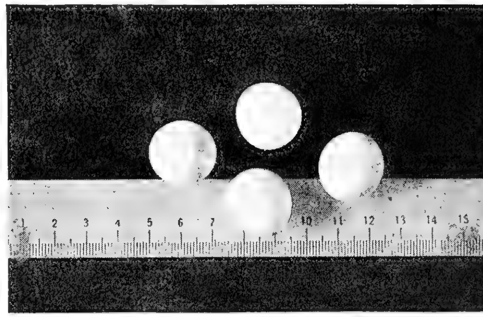

FIG. 17.—Stage 10, 134 miles, $R = .818$

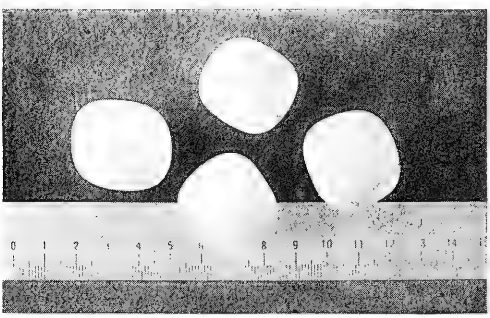

FIG. 15.—Stage 8, 54.5 miles, $R = .550$

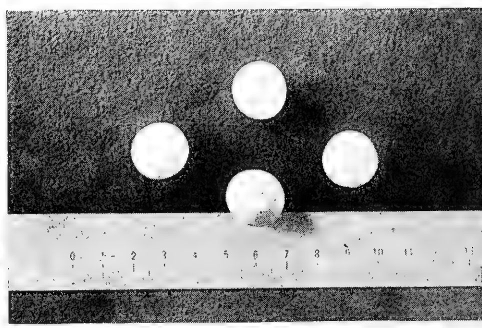

FIG. 18.—Stage 11, 159 miles, $R = .838$

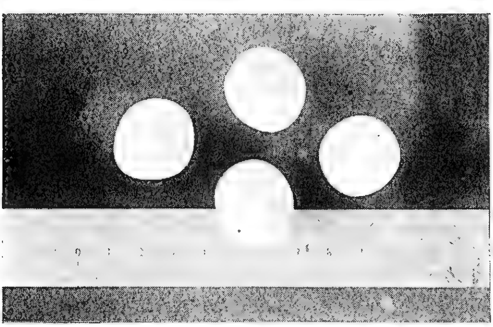

FIG. 16.—Stage 9, 94 miles, $R = .810$

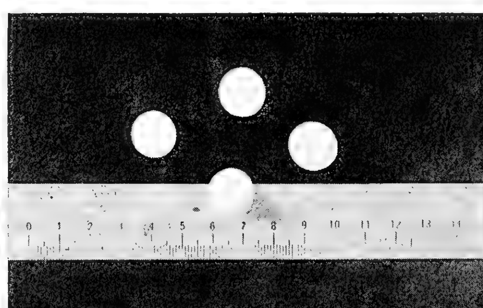

FIG. 19.—Stage 12, 189 miles, $R = .848$

problem, I have used the ratio of the radius of curvature of the most convex part of the surface to half of the longest diameter through that point. This radius is measured with a gauge such as shown in Figure 6 and the diameter with a caliber or usually with a scale with sufficient accuracy.

Figure 7 shows in profile various cobbles with their corresponding values of *R*.

Figures 8–25 show the history of four white marble cubes with the corresponding values of *R*. It will be noted that the four pieces reached a maximum roundness of .862 at an average weight of 3.29 grams and then systematically became somewhat less round as they decreased in size.

Figure 26 is a graph of the roundness as a function of the distance traveled. For this curious increase in angularity with travel I suggest the following interpretation: For any given rock there is

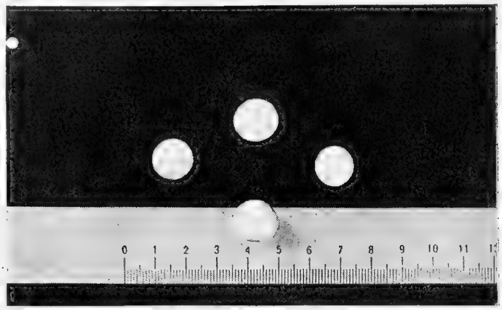

FIG. 20.—Stage 13, 209 miles, $R = .862$

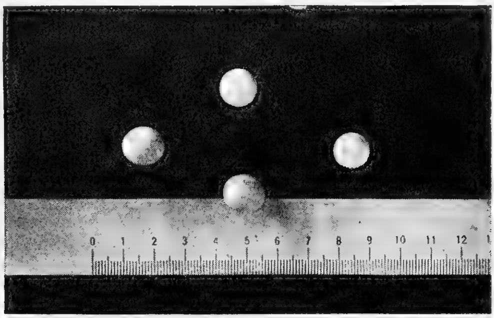

FIG. 21.—Stage 14, 223 miles, $R = .838$

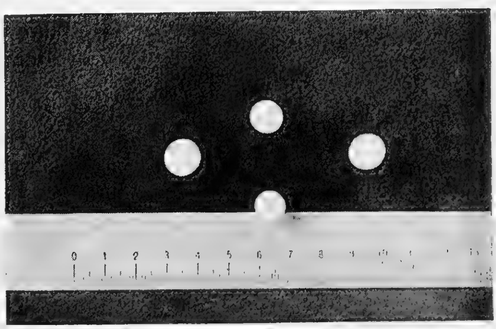

FIG. 22.—Stage 15, 244 miles, $R = .826$

an ellipsoid of equilibrium for wear by abrasion toward which the cobble approaches, which depends on the hardness, or more correctly, durability along various axes.

For a perfectly homogeneous rock this ellipsoid is a sphere; for a non-homogeneous rock it is an ellipsoid of greater or less eccentricity as the case may be and has a greater or less value for *R* in the notation here used. Further, and this is the essential point, this ellipsoid of equilibrium is of different eccentricity for different sizes, more eccentric for smaller sizes than for larger. Thus it is conceived that at 3.29 grams the marble cobbles had nearly or quite reached the ellipsoid of durability for that size and from then on were practically following the equilibrium figure in its decreasing values of *R* as the sizes grew less. This would mean that slight variations in durability between different directions come out more

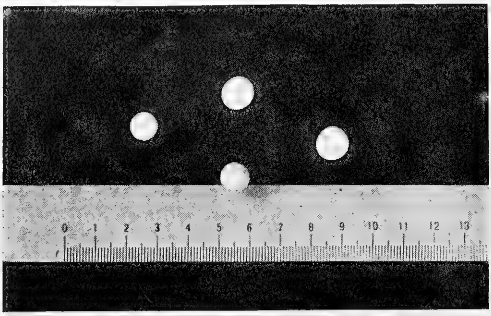

FIG. 23.—Stage 16, 263 miles, $R = .823$

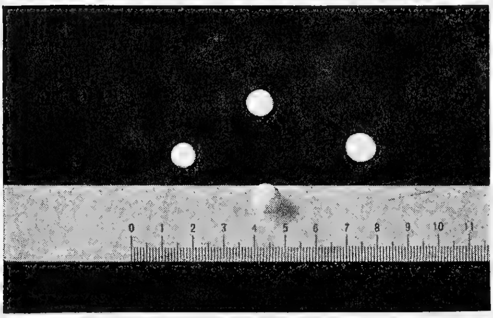

FIG. 24.—Stage 17, 286 miles, $R = .808$

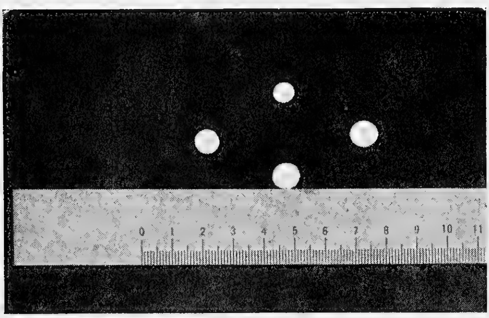

FIG. 25.—Stage 18, 307 miles, $R = .797$

notably in small pebbles than in large, which seems reasonable. This interpretation is put forward as a hypothesis which I hope later to test experimentally in considerable detail.

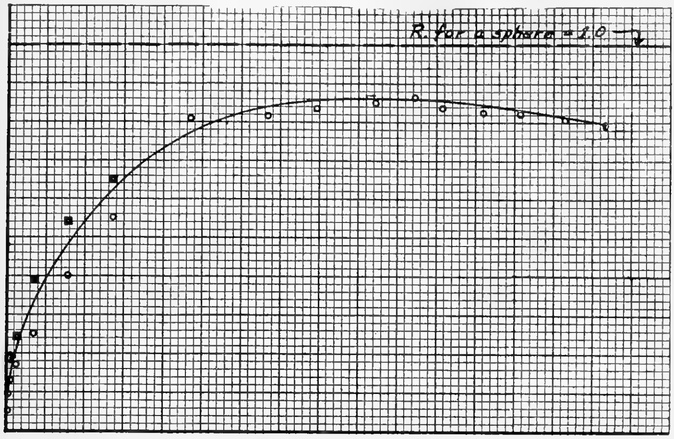

FIG. 26.—Graph of values of R plotted against distance for the series illustrated in Figures 8 to 25.

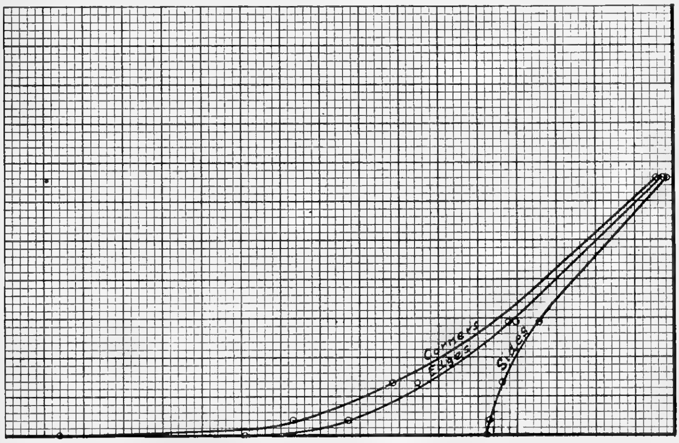

FIG. 27.—Showing convergence of diameters of cubes rounded by cobbles averaging 70 grams each.

8. *Effect of kind of rock on rounding.*—It is hoped later to make studies of the rounding of shaly or schistose rocks whose ellipsoids of

equilibrium would depart notably from spheres, but nothing has yet been done along this line.

9. *Effect of violence of motion on rounding.*—Not yet studied.

10. *Effect of kind of motion on rounding.*—Not yet studied.

11. *Effect of size of cobble on rounding.*—Not yet studied.

12. *Effect of size of associated cobbles on rounding.*—Figures 27 and 28 show the influence of this factor and indicate that large cobbles are much more effective rounding agents than those considerably smaller than the cobble rounded, as shown by the much

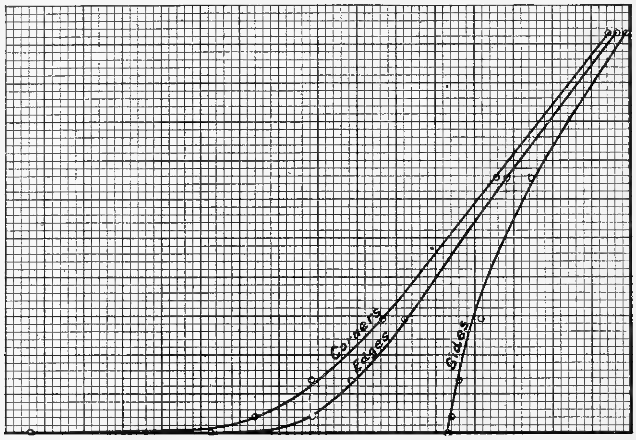

Fig. 28.—Showing convergence of diameters of cubes rounded by cobbles averaging 20 grams each.

slower convergence of the lines in the latter case. It will be noted that the corners and edges lose more rapidly at first (curves concave upward) while the sides lose more rapidly later when their areas are decreased by the wear of corners and edges (curve convex upward). Further studies of this factor are planned.

13. *Effect of kind of rock on surface texture.*—Not yet studied.

14. *Effect of violence of motion on surface texture.*—Not yet studied.

15. *Effect of kind of motion on surface texture.*—Not yet studied.

16. *Effect of size of cobble on surface texture.*—Not yet studied.

17. *Effect of size of associated cobbles on surface texture.*—Not yet studied.

It is hoped that by a study of the crescentic impact scars on some compact quartzites and other rocks an approximate quantitative measure may be made of conditions under which a given deposit was transported and its history thereby interpreted, but no detailed study has been made.

CONCLUSION

Experimental studies, physical or chemical, are of little value to the geologist until they have been applied to actual field conditions. In the studies described and planned above I have tried to keep in mind the possible field applications and hope, as time permits, to point out by field studies the value of each one of the foregoing relations in throwing further light on the past history of the earth. I am especially desirous of receiving opinions on the method of measuring and defining roundness described and used in (17) above, and will appreciate criticism and comment on any other points which have been overlooked or are subject to different interpretation.

CLASSIFICATION OF SPRINGS[1]

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CONTENTS

INTRODUCTION

Among the common phenomena of nature, springs are notable because of their high usefulness. Since the earliest times the homes of men have clustered around them. In arid regions their number and size may limit the population. In many humid regions springs are so numerous and similar that distinctions between them are not recognized, yet they may be caused by so many principal and minor factors or by so many combinations of these factors as to make the origin of any one spring exceedingly complex or obscure. An interesting account of the many erroneous

[1] Published by permission of the Director of the U.S. Geological Survey. The illustrations were prepared by the Survey.

notions held by the ancients regarding the origin of springs can be found in Paramelle.[1] In addition, their very familiarity has brought about an indifference which has led the average investigator to pass them by. Only springs with unusual characteristics have been thought worth study. Elaborate classifications have been suggested for so-called mineral springs—those whose water is exceptional because of gas or mineral content—but a complete classification of all springs has been attempted only by Keilhack.[2] His classes are not mutually exclusive, and his primary division into descending (*absteigende*) springs and ascending (*aufsteigende*) springs separates, not waters of unlike origin, but only waters that have unlike paths to the surface. A number of authors have made incomplete classifications for the springs of a limited region or for some special reason. The principles involved and the names used have been helpful in preparing this classification. Such classifications may be found in the works of Gregory, Meinzer, Fuller, and Johnson, cited in this paper, and in those of Hill and Vaughan,[3] Fournier,[4] and Kilian.[5] References to many articles on springs will be found in Meinzer's bibliography of ground water.[6]

The essential factors in the production of springs are the source of the water and the rock structure which brings it to the surface,

[1] M. l'Abbé Paramelle, *L'art de decouvrir les sources*, 4th ed. (Paris, 1896), chap. xi, pp. 64 ff.

[2] K. Keilhack, *Lehrbuch der Grundwasser und Quellenkunde*, Berlin, 1912.

[3] R. T. Hill and T. W. Vaughan, "Geology of Portions of the Edwards Plateau and Rio Grande Plain Adjacent to Austin and San Antonio, Texas," etc., *U.S. Geological Survey, Eighteenth Annual Report*, Part II *b*.

[4] M. E. Fournier, "Etude sur les sources, les resurgences et les nappes aquiferes du Jura Franc Comtois," *Bull. des Services de la Carte Géol. de la France*, etc. Tome XIII (1901–2), No. 89, pp. 1–55, with 31 figs.

M. E. Fournier, "Etudes sur les projets d'alimentation, le captage, la recherche et la protection des eaux potables," *Bull. des Services de la Carte Géol. de la France*, etc. Tome XIV (1902–3), No. 94, pp. 1–30, 1 fig.

[5] W. Kilian, "Essai d'une monographie hydrologique des environs de Gareoult (Var)," *Bull. de Services de la Carte Géol. de la France*, etc. Tome XVI (1904–5), No. 111, pp. 1–9 with 4 plates.

[6] O. E. Meinzer, "Bibliography and Index of the Publications of the United States Geological Survey Relating to Ground Water," *U.S. Geological Survey, Water-Supply Paper 427*, 1918.

and on these factors the classification outlined in this paper has been based. Temperature, dissolved salts, contained gases, rate and amount of flow, form and position of the spring opening are all characteristics of springs, which, while in many cases related to genesis, vary among springs of the same origin. It has seemed best to first divide springs into two groups based on character of the water and make further subdivisions on structural grounds.

In the use of this classification difficulties will arise which are of two types. In the first place, the local structure in the vicinity of springs is difficult to determine, for the presence and passage of water facilitates weathering and destroys the evidence. The presence of luxuriant vegetation also tends to conceal the structure. Whatever the difficulties of determining the structural relations and origin of the water for single springs, the study of groups of springs will usually be successful. The second difficulty arises through various combinations of structures which may combine to produce a spring. The structure which plays the predominating rôle should then determine the classification of the spring. The common sense and judgment of the investigator will lead him to the proper decision, but his labor will be easier if he remembers that ground water moves through three dimensions, though our conventional methods of illustration show but two. Springs of diverse origin may, however, have peculiarities so remarkable or interesting as to justify their grouping under a common name. The proposed system is not intended to supplant the use of such descriptive terms as blowing springs and thermal springs, but to provide a series of terms expressive of genesis which will include all springs, particularly those now called, for want of a better term, "common springs."

ACKNOWLEDGMENTS

In preparing this paper the writer has profited by the kindly criticism of members of the Ground-Water Club of Washington, D.C. The late Professor Joseph Barrell and Professor Herbert E. Gregory offered helpful suggestions. The writer wishes to acknowledge his special obligations to Dr. Henry Hollister Robinson for his generous help in methods of expression.

DEFINITION OF THE TERM "SPRING"

A spring is a place where water issues from the ground and flows or where it lies in pools that are continually replenished from below, except that wholly artificial openings, such as artesian wells, are not regarded as springs. Many springs have been modified by structures intended to increase their usefulness to man. A seep is a variety of spring in which the water comes, not from any definite opening, but through the pores of the ground over a considerable area. The amount of water yielded by most seeps is small. Many marshes and swamps are actually seeps on a large scale. Large ponds or lakes that are supplied with water through openings in their beds are called spring-fed lakes. A series of seeps and springs may occur along a line, which is then called a spring line. Many local names are used for springs, such as "water hole," "ciénega," and, in New Mexico, "ojo." Names like American Water, Bennet's Wells, Coyote Holes, and Ojo de Gato applied to springs show characteristic usage in the arid Southwest.

The conditions and processes that give rise to springs should be distinguished from those that bring about capillary discharge of ground water. The water of springs and seeps rises under pressure transmitted through the water as it lies as a continuous body in the voids of the rock. On the other hand, capillary discharge is due to molecular attraction between the soil particles and the water, acting against gravity. It takes place because the water is raised from the water table through minute openings in the soil by the force of capillarity and evaporates at or near the land surface. No water is released except by evaporation into the air, whereas the water of springs and seeps forms streams and pools unless the quantity is small and the evaporation excessive. The limit of depth to the water table necessary for capillary discharge to be effective is dependent on the size and uniformity of the soil grains. The limit of capillary rise for most soil is not over ten feet. Many areas that fulfil these conditions are large and well defined—for example, the alkaline flats of arid basins.

CHARACTERISTICS OF SPRINGS

In addition to the rate of flow, other characteristics or peculiarities of springs have given rise to names and classes. None of

these systems of classification are complete enough to include all springs, nor are the classes established even mutually exclusive. The names record only the peculiarities of springs, though these peculiarities may and many of them do arise from diverse causes.

Mineral springs are those which yield water containing in solution (1) unusual amounts of mineral matter, or (2) some uncommon or especially noticeable mineral matter. In distinction other springs are called "common springs." Ground water takes up soluble substances from the rocks through which it flows. In consequence small quantities of soluble matter near the point of emergence of spring water are very effective in changing its composition. Thus mineral content is at best an uncertain guide to the origin of the water or the cause of the spring. Usage also is not consistent. Many "mineral springs" yield water of a type that is common in adjacent regions, but because it is unusual in the immediate neighborhood they are distinguished from "common springs." If the water has or is supposed to have therapeutic value, "mineral springs" are often called "medicinal." Mineral springs are classed according to the chemical composition of the water, and one of the most elaborate classifications is that of Peale.[1]

Some of the simpler and more generally used terms are self-explanatory. Saline springs contain common salt; sulphur springs contain compounds of sulphur, usually hydrogen sulphide; chalybeate springs contain iron; calcareous or lime springs contain calcium carbonate; gypsum or "gyp" springs, gypsum; borax springs, borax, etc. Oil springs contain petroleum suspended in drops in the water. The drops of oil usually rise and form a thin iridescent film on the surface of the water. Inflammable gas may accompany the oil or may occur alone in spring water. Such spring waters have risen through or near beds containing petroleum or natural gas. False oil springs also occur. The iridescent film in these springs is due to iron hydroxide, which at one stage in its formation produces the film. In some springs an oily scum is produced by the decomposition of plants or animals buried but a few inches or feet below the spring opening.

[1] A. C. Peale, "The Natural Mineral Waters of the United States," *U.S. Geol. Survey, Fourteenth Annual Report* (1894), Part II, p. 66.

Springs may be divided according to temperature into thermal and non-thermal springs. Most non-thermal springs have temperatures that are approximately the same as the mean annual temperature of the air of the region in which they are found. The division between thermal and non-thermal waters is usually fixed at 70° F., but 20° to 25° above the mean for the region might be preferable. Thermal springs are usually called "hot," but those of slightly lower temperature are sometimes called "warm." Cold springs have temperatures below normal. The water of some cold springs is derived from the melting of ice or snow; that of others, being quickly transferred from a higher to a lower elevation through open channels, retains the temperature of its point of origin on emergence.

Boiling springs have a sandy bottom, through which the water emerges with some force. The sand is constantly agitated and appears to boil. Bubbling springs, also called boiling springs, are due to the emission of gas or vapor with the water. Certain hot springs actually boil in the ordinary sense. Usually emission of air or gases gives the impression of ebullition. Carbonated springs, which emit carbon dioxide, are the most common bubbling springs. Nitrogen, hydrogen sulphide, sulphur dioxide, marsh gas, and other gases have been found in spring waters. Bubbling is produced also by the emergence of water from a well-defined opening under considerable pressure into a pool of water. The surface of the water is domed, and slight fluctuations in volume or pressure give a bubbling effect.

Perennial or permanent springs flow throughout the year. Intermittent or temporary springs flow only during or after rain. Where evaporation is high the flow of springs is much decreased or may cease during the warm season. Some springs flow only at night because of a very delicate adjustment between supply of water and evaporation. Periodic springs flow at full strength for long or short periods, which are not closely related to the fluctuations in rainfall. The periodic action is dependent on the existence of open cavities. Springs here classed as solution tubular or cavern springs are most likely to have this characteristic. A cavity is drained by a small but insufficient outlet. As water

accumulates it may finally overflow through some higher opening and give rise to a periodic spring. Extreme periodicity of flow however, is attained only when the exit tube acts as a siphon so as to drain rapidly the water that has accumulated in the cavity during a considerable time.

Geysers are hot springs which at regular or irregular intervals emit a stream of mingled steam and hot water. The vent from which eruption takes place usually lies at the bottom of a pool of clear water, situated at the top of a conical mound of siliceous sinter. The sinter is deposited from the water in successive sheets of gelatinous silica, through the aid of living algae.

The geyser consists of a tube of hot water extending into the ground. The temperature of the water at the surface is about 212° F., but that of the water below the surface exceeds the normal boiling-point of water. The water in the lower part of the tube is prevented from boiling by the pressure of the overlying column. When the temperature at any point in the tube exceeds the boiling point for that depth, steam is formed. The expansion and rise of steam bubbles cause the water to overflow at the top. The consequent relief of pressure throughout the column of water causes instantaneous formation of steam from the superheated water. The result is an eruption. Of the water thrown out, part is lost and part returns to the tube. The next eruption occurs after the accumulation of sufficient water and an adequate rise in temperature.[1]

The three known geyser regions of the world are in New Zealand, Iceland, and Yellowstone Park, in each of which the geysers are associated with active or relatively recent volcanism. The heat may be attributed with certainty to still uncooled igneous rock. The water, however, may have either a deep-seated or a shallow origin.[2] Geyser action is not dependent on the origin of the water but on the existence of proper channels and the requisite temperatures. It seems likely that the presence of silica in solution is

[1] Bunsen and Descloiseaux, *Compt. Rend.*, XXIII (1846), 934, and other papers quoted by Archibald Geikie, *Textbook of Geology* (New York, 1902), p. 405; also W. H. Hobbs, *Earth Features and Their Meaning* (New York, 1912), p. 193.

[2] Arnold Hague, "The Origin of the Thermal Springs in the Yellowstone National Park," *Geol. Soc. America Bull.*, XXII (1911), 103–22.

essential to the formation of the tubes. Certainly the waters of all known geysers carry silica in solution in relatively large amounts.[1]

Ebbing and flowing springs occur along the seacoast. During high tide the sea water acts as a dam for the ground water and causes it to flow inland and at higher levels as springs. At low tide the ground-water level falls and the springs are reduced in volume or dry up. On this account the flow of springs adjacent to the shore fluctuates with the tide and may even cease at low tide except close to the shore, where some springs flow only at low tide. Rise and fall of water level due to the same cause have been noticed in wells.[2]

Blowing or breathing springs and wells are characterized by the emission of air, often accompanied by a trumpeting sound. They appear to be due to two causes: (1) rise of the water table, which causes the expulsion of air from cracks and pores of the rock;[3] (2) decrease in barometric pressure, which causes a similar movement.[4] The rise of water brings about blowing at relatively long and irregular intervals, but low air pressure recurs in short cycles.

Mound and knoll springs occur in arid climates. The water emerges at or near the top of a mound which has been built up by the accumulation of wind-blown sand and dust in the belt of vegetation surrounding the spring. The height of the mound is limited by the height to which the water can rise, for any accumulation of sand that is not moist is easily removed because it cannot support the protective vegetation. When the water can rise no higher, the process which builds the mound tends to ceil it over. If the water then finds a new and lower outlet, the mound is drained and subjected to erosion, especially by wind. Mound

[1] F. W. Clarke, "The Data of Geochemistry," 3d ed., *U.S. Geol. Survey, Bull. 616* (1916), p. 196.

[2] A. C. Veatch, "Fluctuations of the Water Level in Wells, with Special Reference to Long Island, N. Y.," *U.S. Geol. Survey, Water-Supply Paper 155* (1906), pp. 10 ff., 63–69. H. B. Woodward, *The Geology of Water Supply* (London, 1910), p. 90.

[3] H. B. Woodward, *op. cit.*, pp. 87–88.

[4] A. Strahan, "The Movement of Air in Fissures and the Barometer," *Nature*, Feb. 15, 1883, p. 375, quoted by Woodward. A. C. Veatch, *op. cit.;* C. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southern Minnesota," *U.S. Geol. Survey, Water-Supply Paper 256* (1911), p. 90.

springs are found in many arid countries in places where water emerges under pressure. Good examples occur in the Tularosa Basin in New Mexico.[1]

Pool springs have large, deep orifices filled with clear water. The pool is surrounded and partly covered with a shelf of fine earth supported by a network of vegetable fibers. The shelf is formed, like mounds, by the growth of vegetation and the filling of the ensuing tangle with wind-blown sand and dust. The two types occur in adjacent springs of the Fish Springs region, Utah, as described by Meinzer.[2] (See also p. 535 and Fig. 3.)

Many springs deposit around their mouths mineral matter that is carried in solution by the water. Calcium carbonate and silica are the most common minerals of spring deposits. Mounds, platforms, and ridges of considerable size are thus formed.

Mud volcanoes—low conical mounds having a crater at the top through which the water rises—are built up when water containing clay or fine sand rises to the surface under pressure. As the water spreads out of the vent it loses velocity and therefore deposits the matter it had carried in suspension. Such deposits are made by the temporary springs formed along fissures in unconsolidated rocks during earthquakes.[3] The emission of volcanic steam and gas through beds of tuff produces the same topographic form. "Salses," "air volcanoes," and "macculutos" are names applied to such springs in different parts of the world. In many of these springs the gases appear to be due to chemical changes in the earth, rather than to volcanism.[4]

SPRING WATER

The waters which circulate in the ground may be roughly divided into two types: (1) deep-seated waters, and (2) shallow waters. The shallow waters are derived largely from precipitation

[1] O. E. Meinzer, "Geology and Water Resources of Tularosa Basin, New Mexico, *U.S. Geol. Survey, Water-Supply Paper 343* (1915), p. 52.

[2] O. E. Meinzer, "Ground Water in Juab, Millard, and Iron Counties, Utah, *U.S. Geol. Survey, Water-Supply Paper 277* (1911), pp. 44–45.

[3] C. E. Dutton, "The Charleston Earthquake of August 31, 1886," *U.S. Geol. Survey, Ninth Annual Report* (1889), pp. 28–284, Plate XX.

[4] Archibald Geikie, *Textbook of Geology* (New York, 1902), p. 407.

at the surface and move through openings, which are generally supercapillary in size. Their movement is due to gravitative pressure transmitted through a continuous body of water, lying in the pore spaces and fractures of the rocks, i.e., by hydrostatic head. Since both kinds of openings decrease rapidly in number and size below 1,500 feet, these waters are limited in amount below that depth. Deep-seated waters have a complex origin. They doubtless include water derived by absorption from the surface, water entrapped in sedimentary rocks at the time of their deposition, and water expelled during the crystallization of igneous rocks. It is believed that these waters do not move because of hydrostatic head, that is, that they are not connected with any overlying and connecting body of water, but that flow is the result of other agencies operative deep within the earth.

Evidence that a spring water has a deep origin may be positive or negative. Thus the water of a spring that has a strong uniform flow not subject to seasonal changes and a high temperature probably has a deep-seated origin. The minimum depth from which the water may come can be roughly estimated from the temperature of the water, on the assumption that there is 1° F. increase in temperature for every 60 to 100 feet of increase in depth. In volcanic regions, however, the increase may be more rapid.

The presence of important breaks in the earth's crust or of other structures along which water could rise furnishes additional positive evidence. Negative evidence is usually easier to obtain and consists of the absence of any structure which could lead the water from the surface to the necessary depth and then return the water again to the surface.

CLASSIFICATION

I. SPRINGS DUE TO DEEP-SEATED WATER

Springs due to deep-seated water may be divided into two classes, according to their geographic distribution, with respect to localities of volcanic or tectonic disturbance. Their relations to the structure of the upper part of the earth's crust and the probable character of the fissures in the zones of fracture which permit the water to rise are shown diagrammatically in Figure 1. In this

figure, no attempt has been made to show the complicated and closely spaced fractures of the upper part of the crust. Only persistent fissures reach the surface, the others merge into the maze of minor fractures and joints.

Volcanic springs are associated with present or past volcanism. This direct association implies that they have their origin either in water expelled from the underlying magma or in surface water that has come into contact with highly heated rocks and has acquired definite characteristics from this association. In general such springs have strong and relatively constant flows and are highly

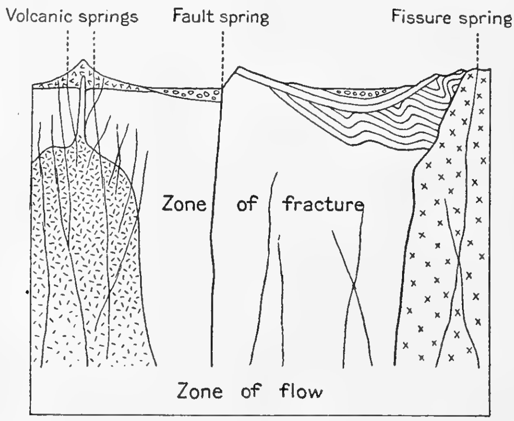


FIG. 1.—Diagram illustrating springs due to deep-seated water

mineralized, and many are gaseous. Some of them have very high temperatures and cannot be sharply divided from volcanic vents emitting steam and gases—fumaroles, solfataras, and mofettes. Others have relatively low temperatures, and many contain carbon dioxide gas. It is generally difficult or impossible to distinguish the latter from springs of non-volcanic origin. The peculiar phenomenon called geyser action characterizes some hot volcanic springs. A typical group of volcanic springs without geyser action lie on the south flank of Lassen Peak, in California (Fig. 2).

The other group of springs due to deep-seated water may be termed fissure springs. In general they have a strong and constant

flow, not subject to annual fluctuations. They are usually warm or hot, and many are highly mineralized. They appear to rise along deep fractures extending far into the crust of the earth. The fractures are similar to those in which were formed the veins now found in mining operations. Doubtless the waters that deposited veins in many places reached the surface as springs.

Certain fissure springs lie along definite lines, and these lines are known to be recent faults involving earth blocks of great depth.

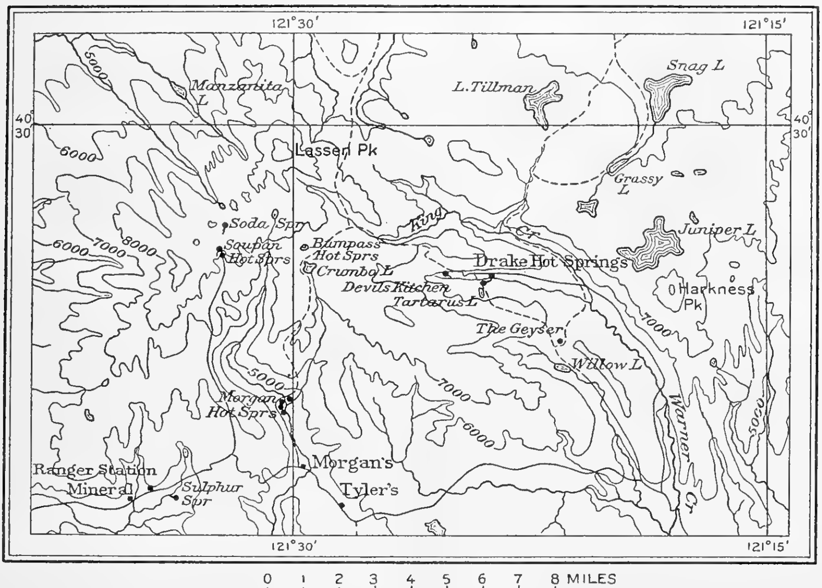


FIG. 2.—Sketch map of Lassen Peak region, California

Faulting appears to produce the fractures which allow these deep waters to rise and carry the temperatures of the deeper crust to the surface. Such springs may be called fault springs. The thermal springs east of the Fish Springs Range, in Juab County, Utah, are a classic example of springs of this type (Fig. 3). The Fish Springs Range is the result of block faulting. The range has a distinct tilt to the west and the fault runs along the eastern flank. Very recent faulting is shown by a fresh fault scarp in the alluvium

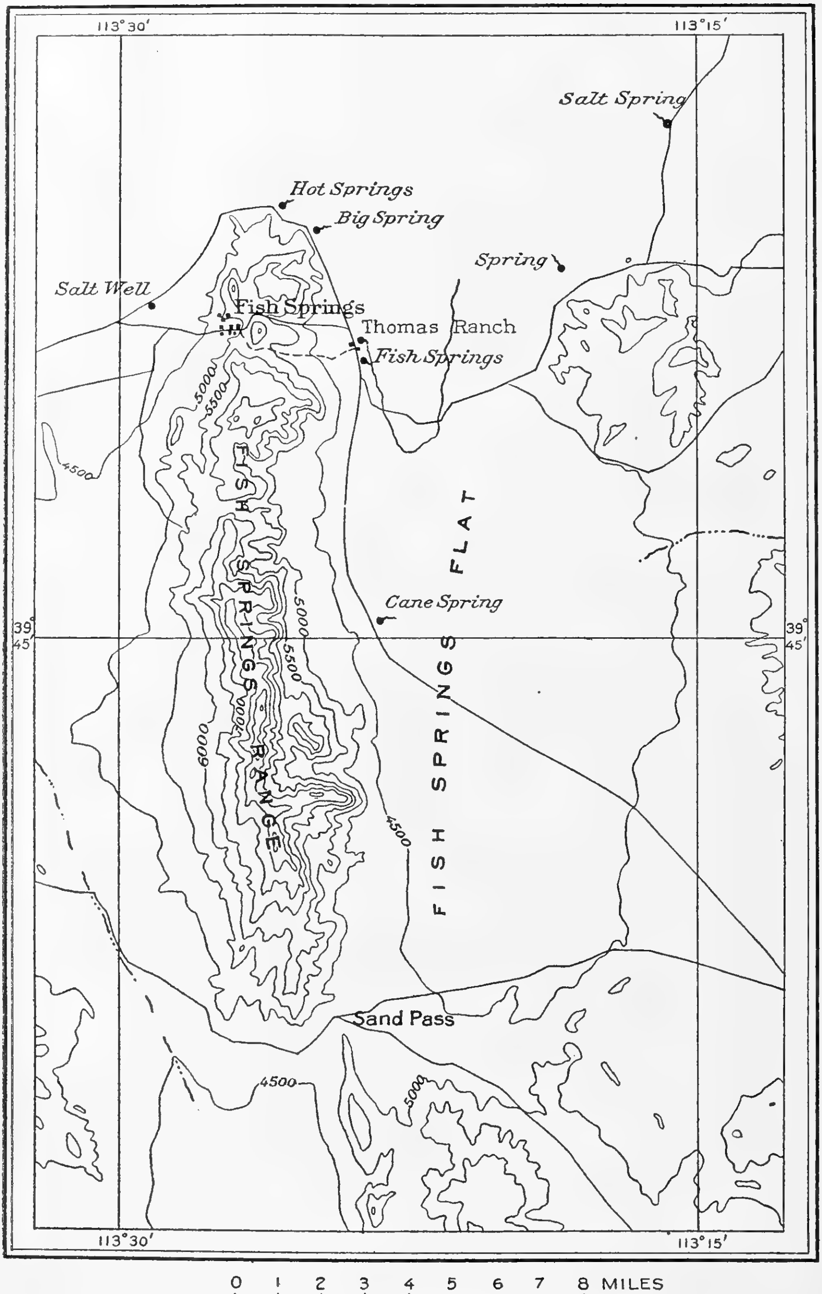


FIG. 3.—Sketch map of Fish Springs Range, Utah

near Fish Springs.[1] Four groups of springs lie east of the range. Hot Springs, Big Springs, and the Fish Springs are on a curving line close to the mountains. They have a steady flow of somewhat mineralized water, and their temperatures are between 78° and 104° F. Cane Spring lies 7 miles south of the Fish Springs group, at the base of the alluvial slope. It consists of a number of seeps of highly mineralized water. Up the slope to the west is the Devil's Hole, a pool of water about 10 or 15 feet below the surface. The form of the pool is similar to those of the Fish Springs group.[2]

Hot Springs, Big Spring, and the Fish Springs are too close to the mountain front to receive much water from the alluvium. Their steady flow and mineralized water imply a deep-seated source, and the recent fault with which they are associated is quite certainly the channel along which they rise. The Cane Spring has the situation of ordinary border springs, but the character of its mineralization and its large volume suggests that part of the water is derived from the now buried southern extension of the same fault. The Devil's Hole may be the last survivor of a group of fault springs whose water has been diverted into the alluvium and rises along the edge of the flat in Cane Spring.

On the other hand, there are fissure springs for whose origin there is no structural evidence. They are believed to have a deep origin because they are not associated with any surface structure that would warrant so strong a flow of water and because of their heated or mineralized condition. Of 98 groups of hot springs in California, 36 occur in granitic rocks.[3] Some of these are fault springs, but others are not directly associated with known faults and can be accounted for only on the supposition that they rise along open fractures or fissures that extend into and draw water from the deeper parts of the earth's crust.

[1] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey, Monograph I* (1890), p. 353.

[2] O. E. Meinzer, "Ground Water in Juab, Millard, and Iron Counties, Utah," *U.S. Geol. Survey, Water-Supply Paper 277* (1911), pp. 43–45, 124–26.

[3] G. A. Waring, "Springs of California," *U.S. Geol. Survey, Water-Supply Paper 338* (1915), p. 154.

II. SPRINGS DUE TO SHALLOW WATER

The pore spaces of the upper crust of the earth are filled with water below a certain level called the water table. This zone of saturation generally has an indefinite extension downward, but in relatively few deep wells is much water encountered below 1,500 feet. Springs due to these relatively shallow waters may be divided into four large groups, according to the character of the rock in which they occur: (1) springs in porous rock; (2) springs in porous rock overlying impervious rock; (3) springs in porous rock between impervious rock; (4) springs in impervious rock.

A. SPRINGS IN POROUS ROCK (DEPRESSION SPRINGS)

Springs in porous rock are formed where the water table or upper surface of the zone of saturation reaches the surface of the ground. Because they are due to the depression of the land surface down to or below the water table, the group may be called depression springs. They are springs whose flow is rather gentle or pools of water that are continually replenished from below. Many are seeps or, if extensive, swamps. They may be divided according to topographic position into four classes, as described in the following paragraphs:

Dimple springs are due to depressions in hillsides which permit the land surface to cut the water table (Fig. 4 *a*). Such depressions or dimples in a sloping surface may arise through erosion by water or wind, through slumping and landslides, through the overturning of trees, or through the operations of burrowing animals, and many are enlarged and deepened by the trampling of larger animals.

Valley springs are due to the abrupt change in slope at the line between the bounding valley walls and the edge of a flood plain (Fig. 4 *b*). Along this line the water table may reach the surface and form seeps or springs. Gullies or low spots between adjacent small alluvial fans may determine the point of emergence. Various causes may enlarge these depressions or may concentrate the flow of the water at specific places, as in the dimple springs.

Channel springs are due to depressions in flood plains or alluvial plains caused by the channel cutting of streams (Fig. 4 *c*). They

thus include all sorts of side channels, abandoned channels, oxbow lakes, sloughs, and water holes. Springs of this type are exceedingly valuable in arid regions. They are frequently made, destroyed, and remade by streams that carry large quantities of sediment.

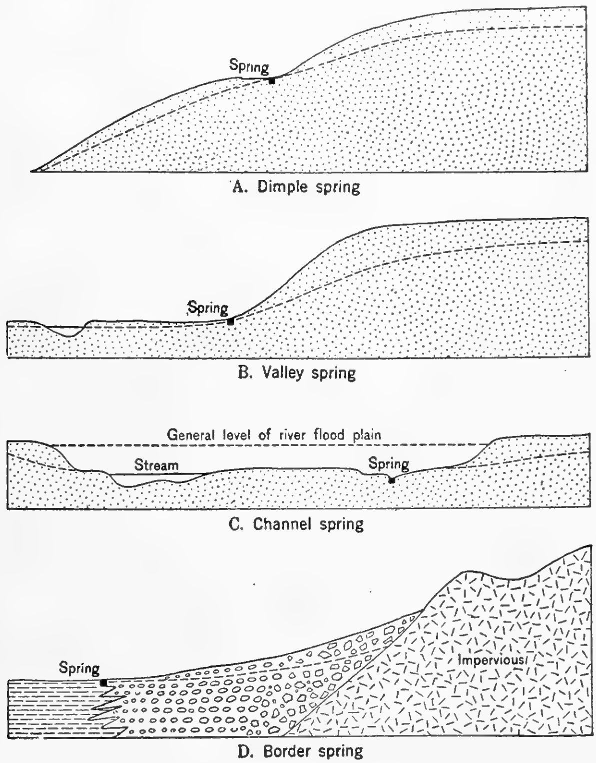


FIG. 4.—Diagram illustrating four classes of depression springs: *a*, dimple springs; *b*, valley springs; *c*, channel springs; *d*, border springs.

Border springs are due to the change in gradient at the line between the alluvial slopes and central flat of a desert basin (Fig. 4 *d*). Such alluvial slopes extend from the mountains with a gradually decreasing gradient. This decreasing slope finally merges with a central undrained flat or with the river bottom of a through-flowing stream. Around the edges of such a flat or the river bottom of a through-flowing stream is a line of springs and seeps.

Ground water is brought to the surface primarily by the change in slope, but the dense silts and clays of the center of the basin tend to act as a dam to prevent further movement down the slope. Thus by their presence they assist the water to rise and may determine the exact location of certain springs. Such border springs are common in the intermontane valleys or bolsons of the western United States. Those of the Big Smoky Valley, Nevada, are shown in Figure 5 and have been described[1] as follows:

> The main west-side spring line of the upper valley extends, with a sinuous course due to the different sizes of alluvial fans, from the Vigus ranch to Wood's ranch, a distance of more than 30 miles, and includes innumerable springs that discharge a part of the copious underground supply received from the Toyabe Range. On the east side of the upper valley there is no spring line comparable to that on the west side, probably because the supply from the Toquima Range is smaller than that from the Toyabe Range, but numerous springs similar to those on the west side are found for a distance of 3 miles in the vicinity of the Charnock ranch.

Concerning the Darrough Hot Springs, which lie along this same line, Meinzer[2] says:

> The water issues from bowldery fill, but probably comes originally from the underlying rock, the heat being due either to igneous intrusion or to faulting that opened deep fissures, or to both causes. Less than 100 feet from the main hot spring and at a level a few feet higher there is a small spring that issues at a temperature of only 60° F., which is almost the normal temperature for this region.

B. SPRINGS IN POROUS ROCK OVERLYING IMPERVIOUS ROCK (CONTACT SPRINGS)

Where porous rock overlies impervious material the water that accumulates in the porous rock is forced to the surface at the contact. Springs so formed may therefore be called contact springs. The form and attitude of the surface of the underlying impervious material divides them into three general types. In one the surface is regular and horizontal, in another the surface is regular but inclined, and in the third the surface is irregular.

[1] O. E. Meinzer, "Geology and Water Resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada," *U.S. Geol. Survey, Water-Supply Paper 423* (1917), pp. 86, 87, Plate II.

[2] *Ibid.*, p. 89.

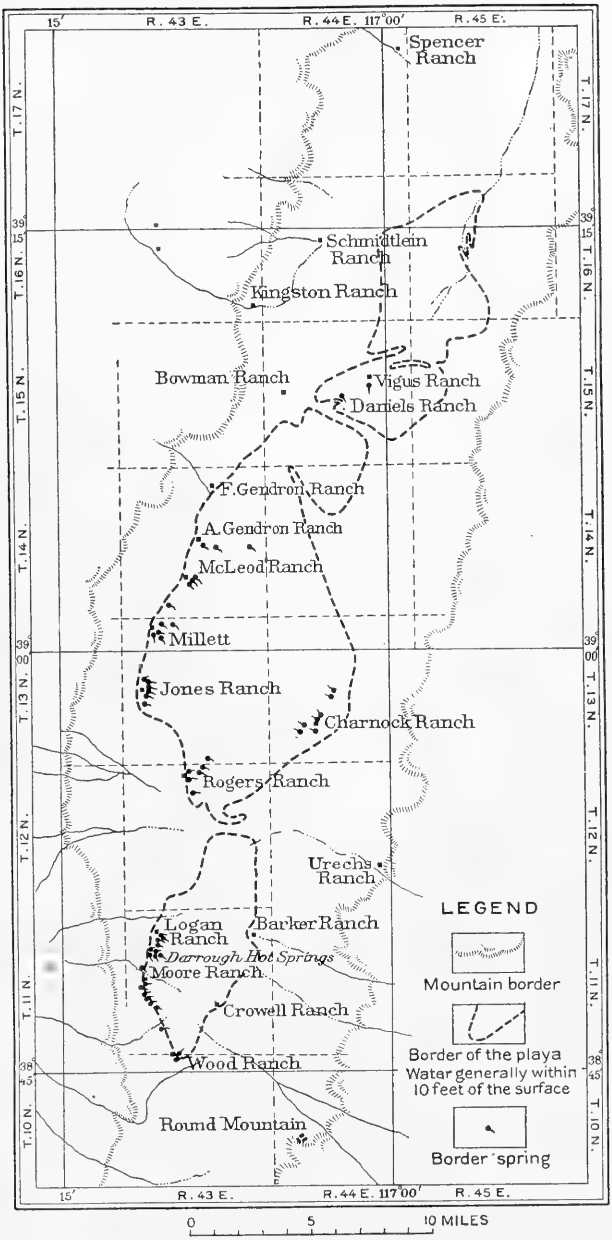


Fig. 5.—Map of the upper Big Smoky Valley, Nevada, showing border springs. (After Meinzer.)

1. *Springs at the outcrop of a horizontal surface.*—Where the impervious rock has a horizontal and regular surface of large extent the rock is usually a member of the sedimentary series of which the overlying porous material is a part. Exceptions, however, occur where the porous material is a surficial deposit but is so regular in its thickness as to give a similar result, or where it is of volcanic origin. There are three classes of these springs.

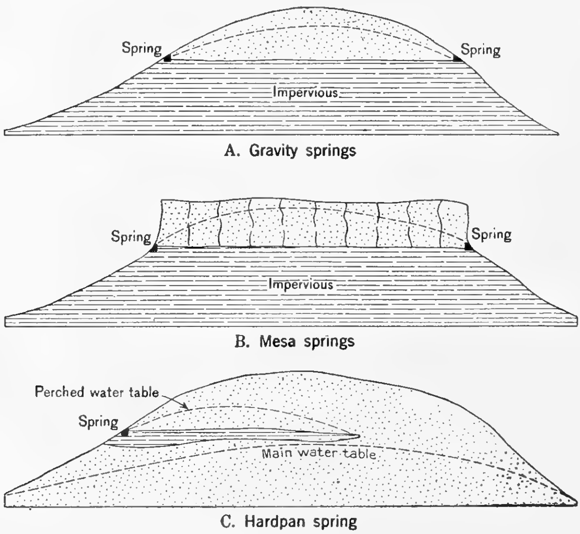


FIG. 6.—Diagram illustrating three classes of contact springs with underlying bed regular and horizontal: *a*, gravity springs; *b*, mesa springs; *c*, hardpan springs.

Gravity springs are those which issue at the contact of a soft and previous bed with an underlying impervious bed (Fig. 6 *a*). The term has been used by Fuller[1] and others. As all springs of the shallow-water type are due to gravity, this term has only the merit of usage. Good examples are Camp Grounds Spring, Crab Tree Spring, and others east of Austin, Arkansas. These springs occur around the edges of the sand-hill area, a ridge of Tertiary rocks on the border of the Mississippi embayment (Fig. 7). Here a thin

[1] M. L. Fuller, "Underground Waters for Farm Use," *U.S. Geol. Survey, Water-Supply Paper 255* (1910), p. 22.

sandstone and sandy clay overlie clay. Water that collects in the sandy beds emerges in a series of springs at the contact with the underlying clay, slightly above the level of the adjacent flood plain of the Mississippi.[1]

Mesa springs are those due to an overlying material which is hard and forms a cliff (Fig. 6 *b*). In this class the overlying material is commonly a sandstone, though it may be a porous and jointed lava flow. Along the east side of Chuska Mountain, New Mexico, in the Navajo country, at an elevation of 8,200 feet, a rough-floored terrace extends for several miles (Fig. 8). Above the shale which floors the terrace a cliff of horizontal Chuska sandstone rises 200 to 500 feet. At the foot of the cliff are more than thirty springs.[2]

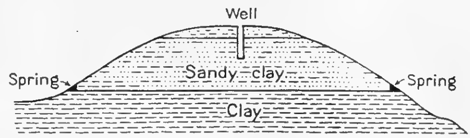


FIG. 7.—Cross-section from Austin to Hickory Plains, Arkansas, illustrating gravity springs. (After Purdue.)

If the underlying bed is of small extent but impervious, it will force water contained in overlying porous material to the surface. In many places such water lies far above the ordinary water table and constitutes what is called a perched water table.[3] Such conditions are fairly common in unconsolidated alluvium. The impervious bed is usually clay, cemented gravel, a "mortar bed," or a layer of caliche or hardpan. As in popular usage all these materials are known as hardpan, springs caused by them may be called hardpan springs (Fig. 6 *c*). The older alluvium of the Sacramento Valley is generally underlain by a bed of reddish hardpan about two feet below the surface. During and after rains water seeps to the surface at the contact of the hardpan with the overlying soil, forming temporary springs. A few springs of this class

[1] A. H. Purdue, "Water Resources of the Contact Region between the Paleozoic and Mississippi Embayment Deposits in Northern Arkansas," *U.S. Geol. Survey, Water-Supply Paper 145* (1905), pp. 93, 113.

[2] H. E. Gregory, "The Navajo Country," *U.S. Geol. Survey, Water-Supply Paper 380* (1916), pp. 140–41.

[3] A. C. Veatch, "Underground Water Resources of Long Island, N.Y.," *U.S. Geol. Survey, Prof. Paper 44* (1906), p. 57.

near Corning, California, in places where the soil above the hardpan is thick and continuous enough to form a reservoir, are permanent.

2. *Springs at the outcrop of an inclined surface.*—If the underlying impervious bed has a regular but inclined surface, all the

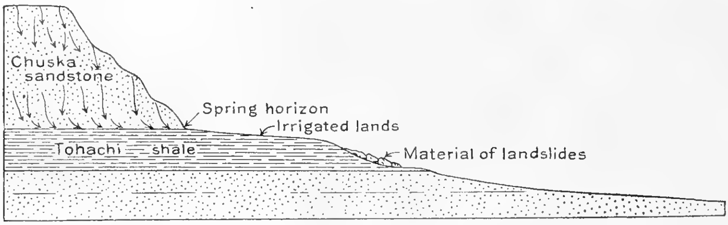


FIG. 8.—Diagram illustrating the conditions producing springs on the east flank of Chuska Mountain, New Mexico. (From Gregory.)

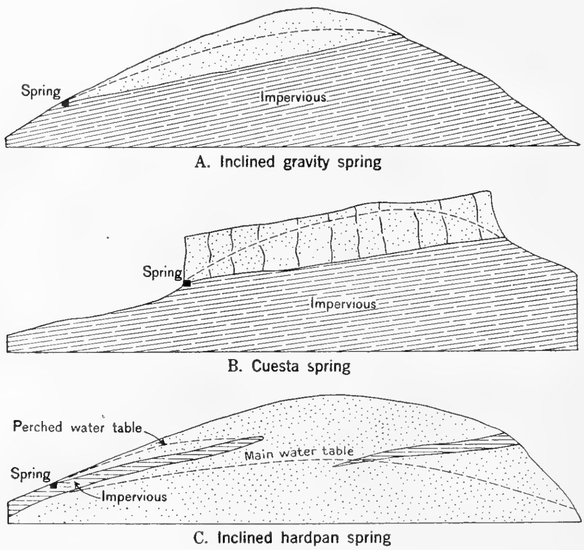


FIG. 9.—Diagram illustrating three classes of contact springs with underlying bed regular and inclined: *a*, inclined gravity springs; *b*, cuesta springs; *c*, inclined hardpan springs.

springs will occur at the outcrop of the contact on the low side, unless the overlying bed is very thick and the dip of the rocks slight. In general, where the underlying bed is of large extent, these conditions exist in sedimentary rocks. Springs of this kind are

divided into two classes, one in which the overlying material is soft and the other in which it is hard. Those of the first class may be called inclined gravity springs (Fig. 9 *a*) and those of the second cuesta springs, after the topographic feature analogous to a mesa (Fig. 9 *b*). Large springs of the inclined gravity type occur near Baden-Baden, Germany (Fig. 10). At this place the lower and middle Buntsandstein, both porous and water-bearing, rest on the smooth erosion surface of the granite. The sandstone has been tilted and eroded into isolated patches. Numerous springs issue along the contact of the sandstone and the granite on the lower side of these erosion remnants. A few springs occur in the talus slopes and on the higher contacts.[1]

Good examples of cuesta springs are those which arise at the contact of basaltic lava and shales of Tertiary age along the western flank of South Table Mountain, north of Oroville, California. The lava is sufficiently jointed and porous to collect water, which runs down the dip of the contact and emerges along the western and lower face of the cuesta.

If the underlying bed is of small extent, springs can only occur where the impervious layer dips with the slope of the hillside but at a smaller angle. These springs are essentially like those in which the impervious layer is horizontal and may also be called hardpan springs (Fig. 9 *c*). The Mountain Mist Springs, in the West Hills, along the northern shore of Long Island (Fig. 11), are of this class. The underlying hardpan is a compact till, and the perched water table lies about 200 feet above the main water table.[2]

3. *Springs at the outcrop of an irregular surface.*—Where the underlying impervious bed has an irregular surface, the overlying material is commonly thin and unconsolidated—a mantle overlying the bed rock. In humid countries the great majority of springs are formed by water that collects in the reservoirs afforded by this porous material. It varies in thickness and character and the irregularities of the underlying surface originate in diverse ways.

[1] H. Eck, "Geognostische Beschreibung der Gegend von Baden-Baden, Rothenfels, Gernsbach, und Herrenalb," *K.-preuss. geol. Landesanstalt Abh.*, neue Folge, Heft 6 (1892), pp. 653 ff.

[2] A. C. Veatch, "Underground Water Resources of Long Island, N.Y.," *U.S. Geol. Survey, Prof. Paper 44* (1906), pp. 57–58.

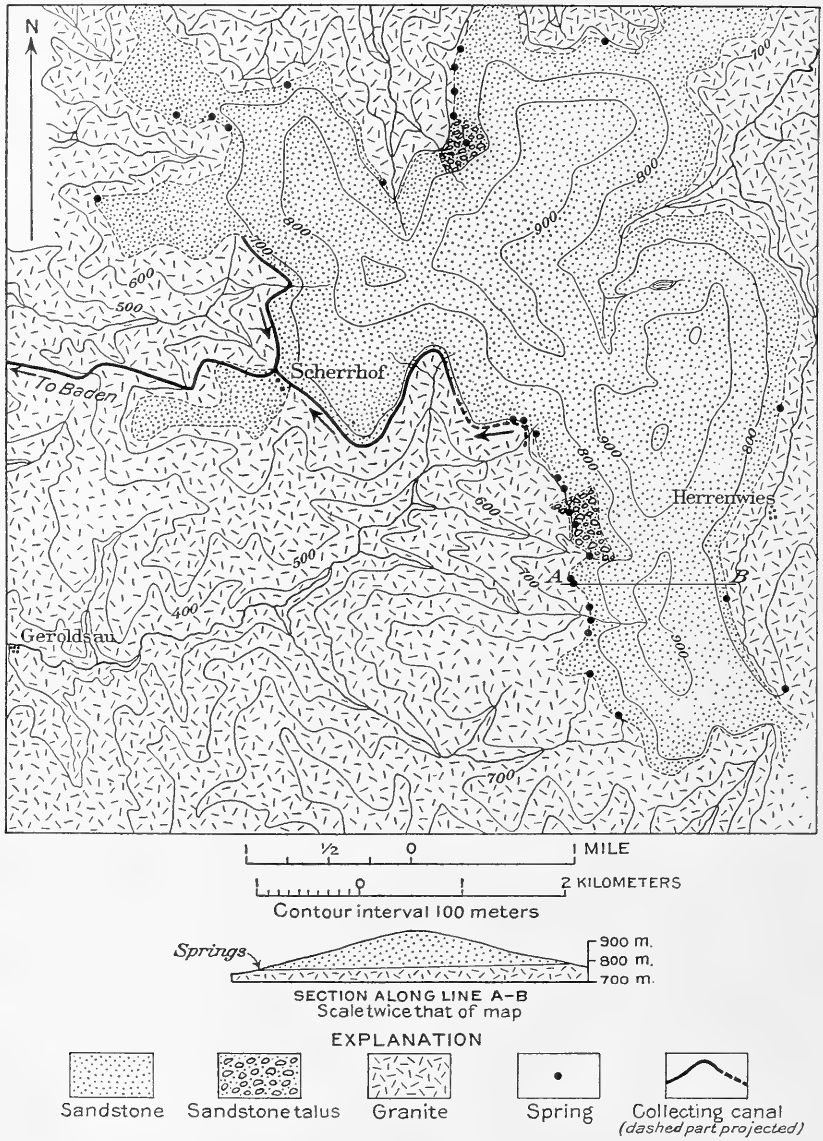


FIG. 10.—Map of an area near Baden-Baden, Germany, showing inclined gravity springs, and connecting canal fed by inclined gravity springs. (Redrawn from Keilhack, after Eck and Lueger.)

Four classes of springs in this group are distinguished in the following paragraphs.

Where the overlying material is thick and of wide extent, the contact is ordinarily an unconformity. The irregularities of such a contact are of minor significance, and here all the types of springs included in the previous group—gravity, inclined gravity, cuesta, and mesa springs—may occur. The springs will be found at the

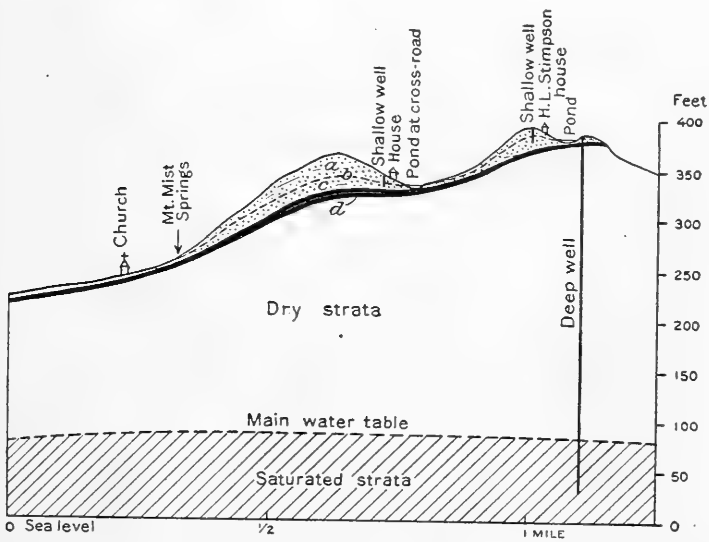


FIG. 11.—Cross-section showing inclined hardpan on the north side of the West Hills, Long Island, New York, and source of Mountain Mist Springs. (After Veatch.)

lowest parts of the contact. Mesa springs that fulfil these conditions occur at the Hopi Buttes, in Arizona (Fig. 12), where the overlying bed is a porous and jointed lava flow underlain by patches of volcanic ash and the underlying impervious beds are tilted and eroded shales and sandstones. The unconformity is fairly smooth, but springs issue in the lowest places.[1]

Where the overlying porous material is localized and the contact is irregular, the resulting springs may be called pocket springs, because the reservoir from which the water is drawn lies

[1] H. E. Gregory, *op. cit.*, p. 139.

in a pocket in the underlying rock (Fig. 13 *a*). The overlying material, which is usually unconsolidated and generally of relatively small volume, may be of different kinds, of which the most common are residual soil, alluvium, till, and wind-blown sand. This is the prevailing type of spring in the till-covered hills of New England and in the soil-covered crystalline rocks of the Sierra Nevada. Most small springs are grouped under this head.

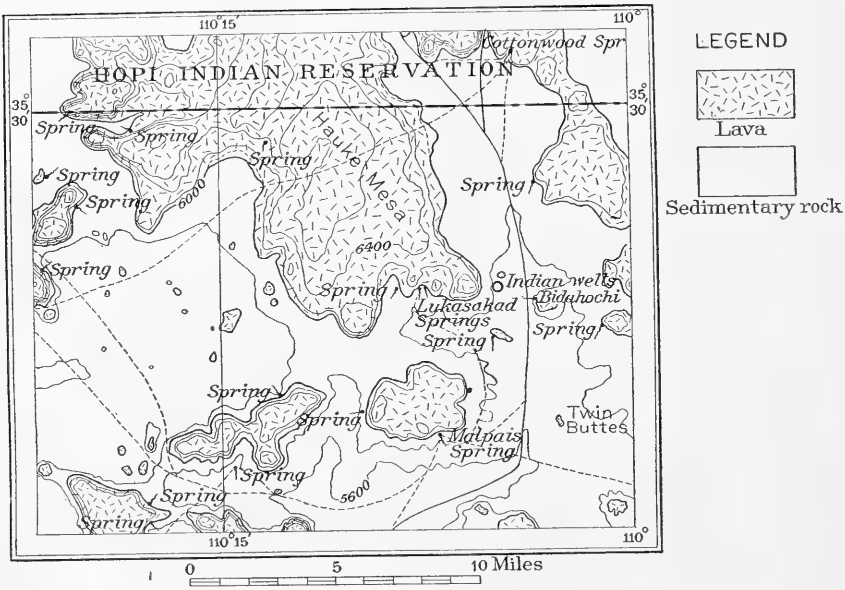


FIG. 12.—Map of a part of the Hopi Buttes, Arizona, showing distribution of mesa springs with reference to lava and sedimentary rock. (From Gregory.)

Pocket springs at the western border of Owens Valley, California, are described by C. H. Lee[1] as follows:

> The springs at the mouth of Sardine Canyon derive most of their supply from the run-off of the drainage area, which sinks into porous gravel deposits in the lower canyon. There is also contribution from accumulations of slide material on the mountain face at the mouth of the canyon. The flow from this group (three springs) varies from 3 to $1\frac{1}{2}$ second-feet.

[1] C. H. Lee, "An Intensive Study of the Water Resources of a Part of Owens Valley, California," *U.S. Geol. Survey, Water-Supply Paper 294* (1912), p. 44 and Plate XXV.

Overflow springs, like pocket springs, are due to the overflow of a reservoir of porous rock (Fig. 13 *b*). The underlying impervious bed is not continuous, but percolation through the porous bed is not sufficient to drain the reservoir. The reservoir is commonly large and of structural origin. These springs are most common in

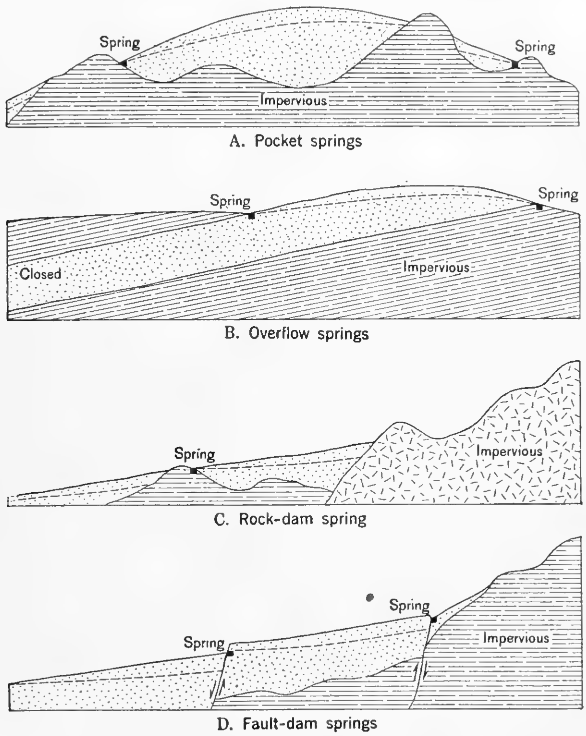


FIG. 13.—Diagram illustrating four classes of contact springs with underlying bed irregular: *a*, pocket springs; *b*, overflow springs; *c*, rock-dam springs; *d*, fault-dam springs.

the collecting area of an artesian system and are distributed along the contacts of the inclosing impervious rocks. An example is found in the North Downs, near London, England (Fig. 14). Many of the springs at this place have ceased to flow because of excessive pumping from wells in the artesian basin to the south.[1]

[1] H. B. Woodward, *The Geology of Water Supply* (London, 1910), pp. 133–35, Figs. 12, 34.

Similar masses of pervious rock may be bounded on one or more sides by impervious rock brought into place by faulting. Overflow will then take place among the fault line, as is exemplified in the northern Vosges Mountains, France[1] (Fig. 15).

In arid regions, particularly, great thicknesses of alluvium have accumulated on irregular rock floors, and if the irregularities of

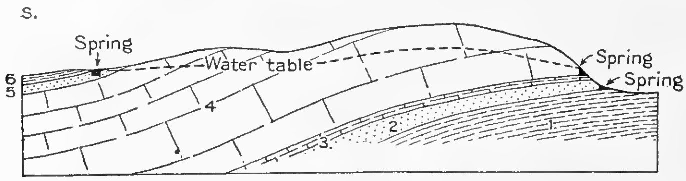


FIG. 14.—Cross-section of the North Downs, near London, England: 1, gault; 2, upper greensand; 3, chalk marl; 4, main chalk, pervious to water; 5, lower London Tertiary strata; 6, London clay, impervious to water. (Redrawn from Woodward.)

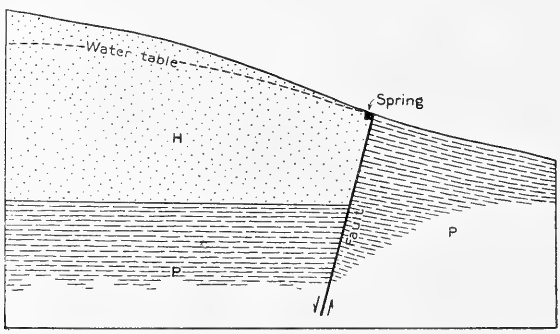


FIG. 15.—Cross-section showing overflow spring in the northern Vosges Mountains, France. H. Hauptbunt-sandstein (porous); P. Rötelschiefer (impervious). (After Leppla.)

the rock floor project through the surface of the alluvial plains, the water contained in the alluvium may be forced to the surface. Essentially similar conditions may be brought about by intrusion of igneous material into such alluvial plains. Under these conditions the rock projections act as dams against the regular flow of the ground water, and the resulting springs may be called rock

[1] A. Leppla, quoted by K. Keilhack, *Lehrbuch der Grundwasser und Quellenkunde*, Berlin, 1912.

dam springs (Fig. 13 *c*). The best-known examples are the ciénegas of the valleys of southern California. West of Cucamonga (Fig. 16) a projection of older cemented alluvium in the Red Hills

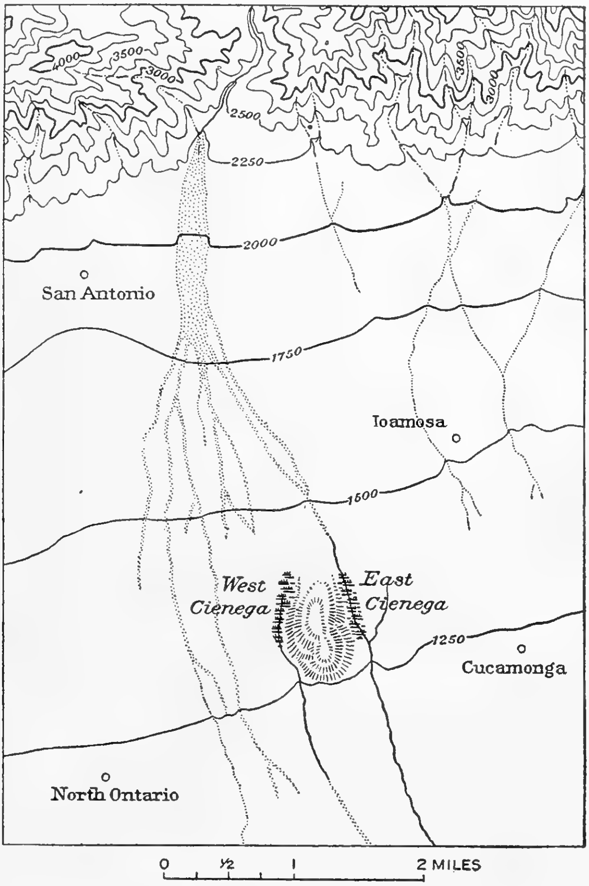


FIG. 16.—Map showing rock-dam springs near Cucamonga, California. (After Mendenhall.)

produces East and West ciénegas; a similar projection of the rocks of the San Rafael Hills produces the springs of Devil's Gate, north of Pasadena.[1] In the Antelope Valley a part of the rock floor of

[1] W. C. Mendenhall, "Ground Water and Irrigation Enterprises in the Foothill Belt, Southern California," *U.S. Geol. Survey, Water-Supply Paper 219* (1908), pp. 34–38, 50–53.

the basin rises above the alluvial plain and produces Lovejoy Springs.[1] Examples of rock dams formed by intrusion of igneous rock into alluvium have not yet been found.

Fault dam springs arise where the free flow of ground water through porous material is interfered with by faulting (Fig. 13 *d*). Fault zones become efficient barriers by the formation of gouge or simply through disturbance and dislocation of the beds. Examples

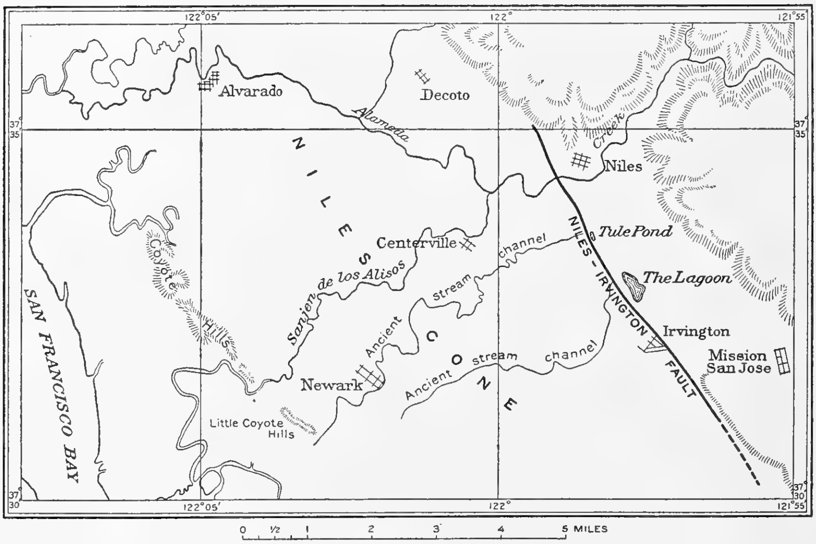


FIG. 17.—Map of the Niles cone, California, showing fault-dam springs due to the Niles-Irvington fault. (After Clark.)

of this class of spring have been found in the Big Smoky Valley, Nevada, by Meinzer.[2] The Niles-Irvington fault, in the Santa Clara Valley, California, beheads an alluvial fan (the Niles cone[3]), as shown in Figure 17. On the side near the mountains the water

[1] H. R. Johnson, "Water Resources of Antelope Valley, California," *U.S. Geol. Survey, Water-Supply Paper 278* (1911), p. 52, Fig. 9.

[2] O. E. Meinzer, "Geology and Water Resources of Big Smoky, Clayton, and Alkalai Spring Valleys, Nevada," *U.S. Geol. Survey, Water-Supply Paper 423* (1917), p. 90.

[3] W. O. Clarke, "Ground Water Resources of the Niles Cone and Adjacent Areas, California," *U.S. Geol. Survey, Water-Supply Paper 345* (1915), pp. 130–32, 150.

table is about 20 feet higher than on the downstream side. Two ponds fed by ground water lie east of the fault. They are fault dam springs.

C. SPRINGS IN POROUS ROCK BETWEEN IMPERVIOUS ROCK (ARTESIAN SPRINGS)

Where water is contained in the pore spaces of a pervious bed lying between impervious strata, the essential conditions for the

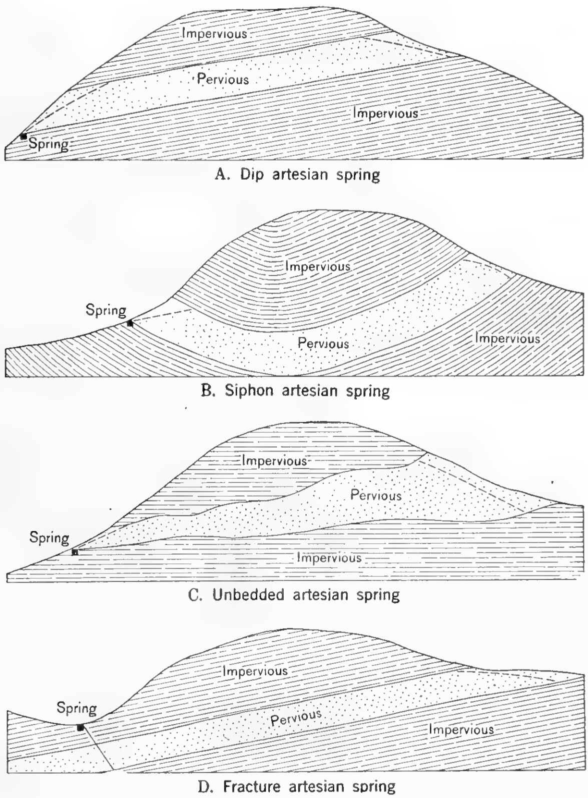


FIG. 18.—Diagrams illustrating four classes of artesian springs: *a*, dip artesian springs; *b*, siphon artesian springs; *c*, unbedded artesian springs; *d*, fracture artesian springs.

existence of springs are that a part of the porous bed outcrop so as to absorb rain in order to provide a regular supply of water, and that the beds be inclined—in other words, the essential conditions

are those of an artesian basin. There are four classes of springs which fulfil these conditions.

Dip artesian springs (Fig. 18 *a*) occur in more or less regularly bedded rocks that have been tilted and eroded in such a manner that the porous bed receives water from the rain or streams in its upper end and that the lower end is exposed at the surface. Sedimentary rocks, alternating lava flows, tuffs and gravels, and unconsolidated alluvial material supply these conditions.

In a series of beds that has been folded, if the proper conditions of inflow and outflow exist, a porous stratum constitutes an inverted siphon for the conveyance of water. Springs due to the outflow from the low side of such a basin may be called siphon artesian springs (Fig. 18 *b*). The artesian basin of the Great Plains is the

FIG. 19.—Cross-section of the Great Plains showing siphon artesian springs near Sioux City, Iowa. (After Darton.)

largest and most remarkable in the world, because of the great distance traveled by the water and the heavy pressure under which it exists. Along the eastern border of the basin the beds have a distinct westward tilt, but the water-bearing Dakota sandstone is not everywhere exposed (Fig. 19). However, near Sioux City, Iowa, numerous springs and seeps are found along the western bluffs of Missouri River, where the Dakota first emerges from beneath its impervious cover.[1]

In certain unconsolidated deposits not regularly bedded, a mass of porous material may be so exposed as to receive water at a high level and discharge this water at a lower level. The springs resulting from this structure may be called unbedded artesian

[1] G. E. Condra, "Geology and Water Resources of a Portion of the Missouri River Valley in Northeastern Nebraska," *U.S. Geol. Survey, Water-Supply Paper 215* (1908), pp. 27, 28.

springs (Fig. 18 *c*). Though rare, springs of this class occur in till, and doubtless examples may be found in other types of rock.

The springs of the three classes just described depend on the outcrop of the saturated porous bed in its lower portion. Springs occurring where the porous bed does not crop out, but the water escapes from it by an opening leading to the surface, may be termed fracture artesian springs (Fig. 18 *d*). Many of these springs have been classed with fissure springs, but it seems essential to distinguish between springs that tap artesian basins and yield water under hydrostatic head, and those that depend on the deeper waters of the crust. This name is chosen because it seems probable that all such openings are primarily fractures in the rocks. Although it is true that great pressure is exerted by the water in deep artesian basins, it seems improbable that pressure could force water to rise through overlying material in sufficiently definite channels to supply springs unless it moved along pre-existing faults or other fractures. Water pressure may assist in keeping the fracture open, and the flow of water tends to plaster up caving walls with mud, as in the hydraulic systems of drilling wells, or to solidify them with precipitated minerals. Many of the springs of this class have a high temperature, a steady flow, and an alignment that causes them to be confused with true fault springs. However, a distinction should be made. If definite artesian structure can be demonstrated, most of the water is probably meteoric in origin—that is, it is derived from rain or melted snow absorbed at the outcrop; if artesian structure cannot be demonstrated, there is a strong presumption that much of the water arising along great faults and deep fractures in the crust is of juvenile origin—that is, it issues from deep within the earth and now sees the light of day for the first time. At any rate, there is a sufficiently distinct difference in structure to justify separate classification of the springs.

In Antelope Valley, California, porous sand and gravel underlying clay contain water under artesian pressure. Numerous wells have been sunk to obtain this water, and its chemical character and temperature are known. Buckhorn, Indian, Willow, and other springs having water similar in character and temperature

lie along a fault at the foot of Rosamond Buttes but probably not exactly on the fault trace (Fig. 20). This fault is represented by an escarpment in the alluvium west of Willow Springs, from 50 to 100 feet in height and extending for a distance of 5 miles.[1] The

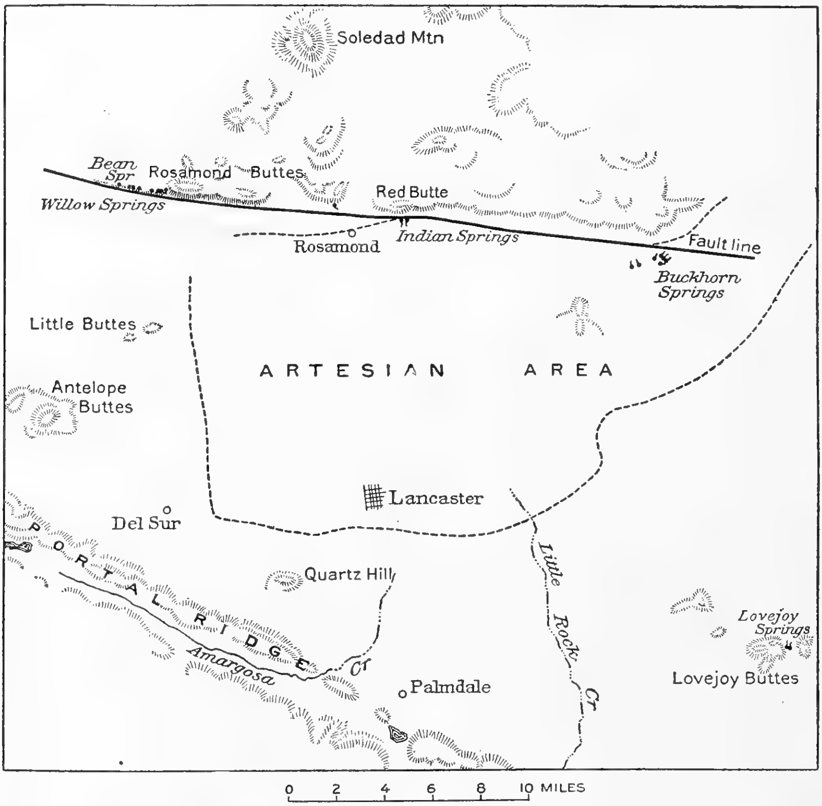


FIG. 20.—Map of Antelope Valley, California, showing fracture artesian springs. (After Johnson.)

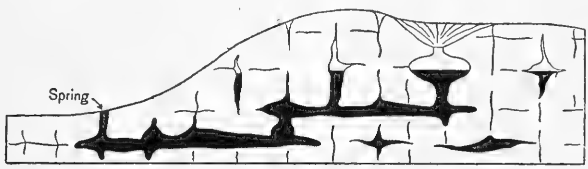
irregular alignment of these springs is best explained by assuming that there are associated with the main fault a number of subsidiary but parallel fractures which permit the artesian water to rise. Alternative explanations are offered by Johnson, but the absence of springs except along this general line makes other

[1] H. R. Johnson, *op. cit.*, pp. 21 and 49.

explanations improbable. These springs, therefore, may be taken as typical of the class of fracture artesian springs.

D. SPRINGS IN IMPERVIOUS ROCK

The term porous and impervious are of course relative, but impervious rocks may be considered to have pore spaces of capillary or smaller size, which usually form a relatively small percentage of the rock. Some clay, however, has a high porosity but because of the absorption of water and swelling of individual grains is highly impervious. Through such pore spaces effective flow under hydrostatic head is impossible. Movement takes place



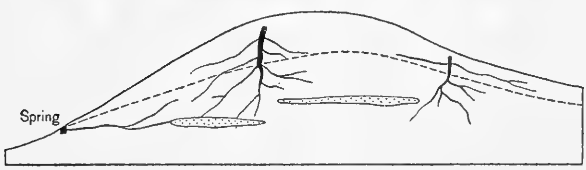


FIG. 21.—Diagram illustrating two classes of tubular springs: *a*, solution tubular springs; *b*, minor tubular springs.

through openings which may be grouped into two types: (1) those which are more or less tubular in form, and (2) those which are sheetlike in form and along which the water moves as a thin film.

1. *Tubular Springs.*—Springs of the first group may be called tubular springs. This group can in turn be divided into three classes, according to the origin of the tubular openings. Solution tubular or cavern springs are due to channels and openings formed through solution of the rock by circulating ground water (Fig. 21 *a*). Solution commonly begins along joints or other previously existing openings, and the channels may be enlarged to a very great size. In these tubes the water then flows freely and with relative rapidity.

The rocks that are affected by this process are limestone, calcareous sandstone, gypsum, and salt. Silver Spring, in Marion County, Florida, is a well-known example. This spring emerges from several openings in the cavernous Vicksburg limestone into a pool several acres in extent. The volume of flow is about 385,000 gallons a minute, or 855 cubic feet a second, a stream sufficiently large to float a steamer.[1]

Lava tubular springs are due to caverns and tunnels in lava flows. These caverns and tunnels are formed through the process of igneous extrusion. When a very liquid lava cools rapidly, a crust of sufficient strength to support itself may form on the surface and the liquid lava below may flow out, leaving an arched tube. Under other conditions the crust may yield to lateral pressure of the underlying liquid lava and form arched tunnels which are made permanent by the solidification of the lava. Principally by these two processes caverns and tunnels may be produced in formations due to successive lava flows, and under favorable circumstances such openings may form channels for the ground water. On the southern flank of the mountain mass which culminates in Lassen Peak, California, large springs break out in Big Meadows, about 5 miles from Prattville.[2] The water issues from basaltic lava in an area about 100 yards in diameter. The flow is 29,000 gallons a minute, or 62.6 cubic feet a second, and the temperature is 46° F. The springs belong to a series characteristic of the lower slopes of the Lassen Peak mass, and a few of them are shown in Figure 2 (p. 533). The low temperature of these springs indicates that the water originates high up on the mountain and flows rather quickly down the slope. It seems probable that the water flows through caverns and tunnels in the lava rather than through the pores of the rock. This interpretation is supported by the existence of a similar series of springs around Mount Shasta. Plutos Cave, north of this mountain, is an example of the kind of caverns through which the water passes. It is in places 60 feet high and 50 feet wide and

[1] G. C. Matson and Samuel Sanford, "Geology and Ground Waters of Florida," *U.S. Geol. Survey, Water-Supply Paper 319* (1913), p. 367.

[2] G. A. Waring, "Springs of California," *U.S. Geol. Survey, Water-Supply Paper 338* (1915), p. 330.

has been explored for more than a mile.[1] Certain cold springs on Mount Shasta, however, appear to be due to the melting of buried ice.[2]

Minor tubular springs are due to a variety of causes (Fig. 21 *b*). The tubes or channels are of small size and irregular length, and many of them appear to be due, at least in part, to the movement

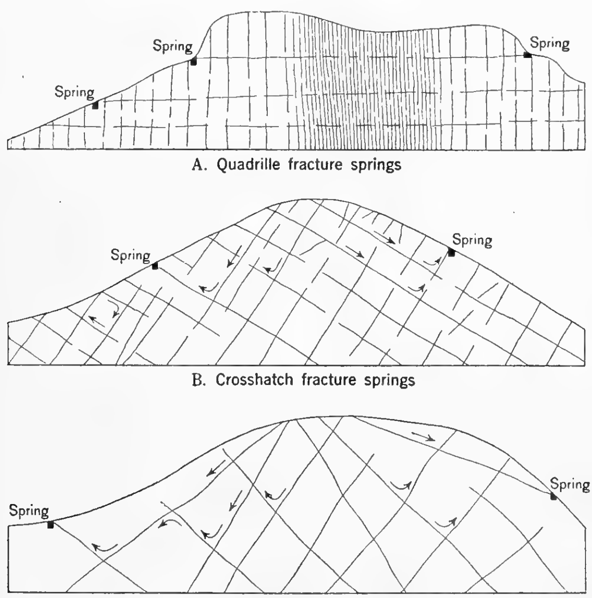


FIG. 22.—Diagram illustrating three classes of fracture springs: *a*, quadrille fracture springs; *b*, crosshatch fracture springs; *c*, inclined fracture springs.

of the water itself. Unconsolidated deposits are particularly susceptible to this action. The decay of plant roots, the existence of small sand streaks, and the enlargements of shrinkage cracks may all assist in the production of these minor openings.

2. *Fracture springs.*—Springs that issue from sheetlike or platelike openings in non-porous rocks may be called fracture springs, because such openings are primarily due to fractures. Joints,

[1] H. W. Fairbanks, *Practical Physiography* (Boston, 1906), p. 178, Fig. 180.

[2] G. A. Waring, *op. cit.*, p. 332.

bedding planes, faults, columnar joints, and openings formed on slaty cleavage, fissility, and schistosity are the common types of fractures in igneous and metamorphic rocks. In sedimentary rocks joints, bedding planes, cross-bedding planes, and faults are the principal types of fractures. If the fractures are very numerous and closely spaced, however, water moves through the rock in essentially the same fashion as in porous rocks. Minute fracture systems add very much to the effectiveness of interstitial pores and are probably present in all porous rocks. The essential difference is that in a porous rock water moves bodily, and, as a rule, slowly

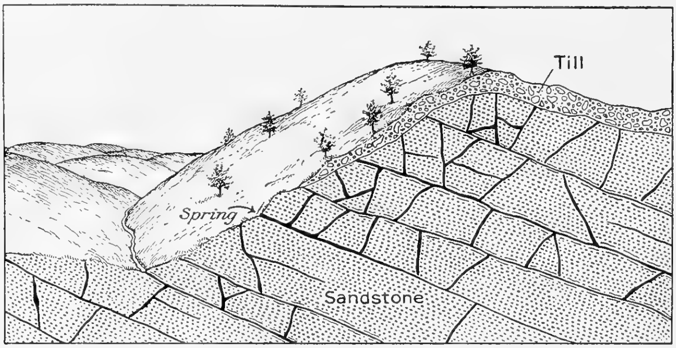


FIG. 23.—Diagram showing occurrence of springs near Mount Carmel, Connecticut. (After Gregory.)

through minute openings, whereas in fractured impervious rocks it moves more rapidly as sheets, threads, or films of water.

Fracture springs may be divided into two classes according to the attitude of the fractures toward one another and toward the horizon. A common joint system is one in which there are two or three sets of joints at right angles to one another and one of the sets is horizontal. Springs due to such joints may be called quadrille fracture springs (Fig. 22 *a*). Such a jointing system is common in sedimentary rocks and in impervious igneous rocks, particularly in sheeted plutonic rocks. Springs due to two systems of joints at right angles to each other and inclined to the horizon may be called crosshatch fracture springs (Fig. 22 *b*). Joints and bedding planes in Triassic sandstones form such a system of

fractures and give rise to springs near Mount Carmel, Connecticut, as shown in Figure 23.[1] Far more abundant, however, are irregular systems of joints, all of which are inclined toward the horizon, and springs due to such systems may be called inclined fracture springs (Fig. 22 *c*).

KEY TO THE CLASSIFICATION OF SPRINGS

I. Springs due to deep-seated waters, juvenile and connate, admixed with deeper meteoric water; do not flow under hydrostatic head and are usually not subject to seasonal fluctuation.

- A. *Volcanic Springs.* Associated with volcanism or volcanic rocks; water commonly hot, highly mineralized and containing gases. Grade from gas vents into springs of normal temperature indistinguishable from those due to other causes.
- B. *Fissure Springs.* Due to fractures extending into deeper parts of the crust; water usually highly mineralized and commonly warm or hot.
  1. Fault Springs. Associated with recent faults of great magnitude.
  2. Fissure Springs. No direct structural evidence as to origin, but because of temperature and steady flow believed to have deep origin.

II. Springs due to meteoric and occasionally other waters moving as ground water under hydrostatic head; many fluctuate in flow with the rainfall.

- A. *Depression Springs.* Due to land surface cutting water table in porous rocks.
  1. Dimple Springs. Due to depressions in hillsides.
  2. Valley Springs. Due to abrupt change in slope at edge of flood plain.
  3. Channel Springs. Due to depressions in flood plains or alluvial plains caused by channel cutting of stream.
  4. Border Springs. Due to change in slope at border between alluvial plains and playas, lake beds, or river bottoms; relative imperviousness of central clay deposits assists flow.
- B. *Contact Springs.* Due to porous rock overlying impervious rock.
  1. Impervious rock has a horizontal and regular surface.
     - *a*) Underlying bed is of large extent; common in consolidated sedimentary rock.
       - (1) Gravity Springs. Overlying material is soft.
       - (2) Mesa Springs. The overlying material is hard, usually sandstone or lava flow; water contained in pores and joints of the rock.

[1] H. E. Gregory and E. E. Ellis, "Underground Water Resources of Connecticut," *U.S. Geol. Survey, Water-Supply Paper 232* (1909), p. 136.

b) Underlying bed is of small extent; common in unconsolidated alluvium; impervious bed is usually clay, cemented gravel, "mortar bed," caliche, or hardpan.
   (1) Hardpan Springs.

2. Impervious bed has an inclined and regular surface; all springs on the low side unless the overlying bed is very thick and the dip low.
   a) Underlying bed is of large extent.
      (1) Inclined Gravity Springs. The overlying material is soft.
      (2) Cuesta Springs. The overlying material is hard; of same character as mesa springs.
   b) Underlying bed is of small extent; as in hardpan springs.
      (1) Impervious layer dips away from hill; spring possible.
      (2) Impervious layer dips into hill; spring possible only in ravines.

3. Impervious bed has irregular surface.
   a) Overlying porous material is thick and of wide extent; contact is unconformity. Gravity, inclined gravity, mesa, and cuesta springs may occur, but springs will be sharply localized at lowest parts of contact.
   b) Pocket Springs. Overlying porous material is unconsolidated and more or less discontinuous, residual soil, talus, landslide débris, alluvium, till, stratified drift, wind-blown sand, or volcanic ash.
   c) Overflow Springs. Irregular floor is not continuous, but porous bed is saturated and overflows at lateral contacts; common at receiving end of artesian systems.
   d) Rock Dam Springs. Irregularities of the rock floor under an alluvial plain force water to surface; these may be projections of floor of basin, projections of partly consolidated older alluvium, igneous dikes, or volcanic plugs.
   e) Fault Dam Springs. Dam caused by faulting.

C. *Artesian Springs.* Due to pervious bed between impervious materials.

1. Dip Artesian Springs. More or less regularly bedded rocks; tilted porous bed crops out in valley; usually sedimentary, also alternations of lava flows, flow breccias, tuffs, gravels.
2. Siphon Artesian Springs. Similar rocks; folded and with outcrops in valley.
3. Unbedded Artesian Springs. Rocks not regularly bedded, but mass of porous material is exposed so as to receive water and crops out in valley; occur in till and perhaps in other rocks.

4. Fracture Artesian Springs. All the conditions above, except that lower end of porous bed does not crop out but an opening allows water to escape. Opening due to fracturing with or without faulting.

D. *Springs in Impervious Rock:*

1. Tubular Springs. Due to more or less rounded channels in impervious rocks.
   - *a*) Solution Tubular or Cavern Springs. Due to solution channels in limestones, calcareous sandstones, gypsum, salt.
   - *b*) Lava Tubular Springs. Due to caverns and tunnels in lava flows.
   - *c*) Minor Tubular Springs. Due to channels made by movement of water, decay of tree roots, sand streaks, or shrinkage cracks, usually in unconsolidated sediments.
2. Fracture Springs. Due to fractures consisting of joints, bedding planes, columnar joints, openings due to cleavage, fissility, schistosity, cross-bedding planes, and faults in impervious sedimentary, igneous, and metamorphic rocks.
   - *a*) Quadrille Fracture Springs. Due to more or less rectangular system of fractures, one of which is parallel to the horizon.
   - *b*) Crosshatch Fracture Springs. Due to more or less rectangular system of fractures, inclined toward the horizon.
   - *c*) Inclined Fracture Springs. Due to inclined fractures, not necessarily systematic.

AEQUINOCTIA, AN OLD PALEOZOIC CONTINENT

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Through the whole of Central Celebes,[1] from the Gulf of Boni to the Gulf of Tomini, extends a formation of crystalline schists, lying east, but principally west, of Lake Posso. These schists are strongly folded and their positions vary from horizontal to vertical. More than once, but last during the Oligocene, this region was leveled by denudation. The resulting peneplain was arched during the neo-Tertiary and Plio-Pleistocene to 2,000 meters above sea-level. Consequently, it became deeply cut by erosion. In some of these furrows one can distinctly observe an east-west strike of the strata, which seems to be the effect of the oldest folding. Especially on the west of Lake Posso the region appears now as a distinct geographical entity. West of these mounts others follow, either separated from the first by depressions or not. They consist of gneiss, viz., biotite and amphibole gneiss, amphibolites, granites, and effusive rocks. In this part of the country the peneplain character has not been preserved so well; the highest tops reach altitudes up to 3,000 meters.

In no other part of the Dutch East Indian Archipelago do the gneiss and schists region occupy such a large surface as in Central Celebes; besides that, the crystalline schists are characterized by a particular richness of rock varieties.

Most of the schists belong to the second and eighth groups of the Grubenmann[2] classification, and to the upper and middle zones of these groups. This leads to the conclusion that they represent metamorphosed clays, sandstones, and argillaceous sandstones. Besides these rocks, a certain importance must be attributed to the metamorphosed calcareous sandstones and limestones, rocks of the

[1] See E. C. Abendanon, *Voyages géologiques et géographiques à travers la Célèbes Centrale*, 3 volumes and one atlas, Leyde, Holland, 1916–18.

[2] U. Grubenmann, *Die kristallinen Schiefer*, Vol. II, 1907.

ninth and tenth groups, some of them making part of the upper zone, but chiefly belonging to the middle zone. These latter varieties appear principally along the eastern bank of Lake Posso and north of the lake.

With these schists of sedimentary origin, there are others which must have evolved from more or less basic eruptive rocks and their tuffs. But for a few exceptions, belonging to the middle zone, most of these latter schists belong to the upper zone; they are represented by rocks of groups three (plagioclase gneiss), four (metamorphosed gabbroid rocks), and five (schists containing silicates of magnesia).

The age of this formation of schists in Central Celebes and in other parts of the archipelago has been interpreted as follows:

1. Wichmann[1] considers the mica schists of Central Celebes as Archean; Martin[2] does the same regarding those of Ceram, whereas Verbeek[3] thinks that those of South Borneo constitute a series of Azoic rocks; Volz[4] refers to the Archean only the gneiss of the land of the Gajôs (North Sumatra).

2. Molengraaff[5] believes that the crystalline schists of Central Borneo are partly Archean, partly of more recent age.

3. Verbeek[6] groups the gneiss and mica schists which he found in the Moluccas, with other rocks, such as the quartzites (of dark color) and argillaceous schists, in the "old schists formation," in which he presumes the existence of Azoic (e.g., the gneiss of Sibelaboe) or Archean elements, but also elements of the Old Paleozoic. His opinion upon this matter is shared by Volz[7] and Ahlburg,[8] who also connect other rocks, such as the peridotite of eastern and southeastern Celebes, with the mica schists. Volz draws attention to the complete conformability between the mica schists and the old schists in the aforementioned land of the Gajos. It must be

[1] "Der Posso-See in Celebes," in Petermann's *Geogr. Mitteilungen*, Heft VII, 1896.

[2] "Reisen in den Molukken," *Geologischer Theil*, 1903.

[3] *Jaarboek van het Mijnwezen*, Vol. I, 1875.

[4] *Nord-Sumatra*, Vol. II, 1912.

[5] *Geologische verkenningstochten in Centraal. Borneo*, 1900.

[6] *Rapport sur les Moluques*, 1908. [7] *Nord-Sumatra*, Vol. I, 1909.

[8] *Versuch einer geologischen Darstellung der Insel Celebes*, 1913.

remarked that a similar conformability has been discovered nowhere else in the archipelago by any of the other explorers.

4. The rare true mica schists of Letti are regarded by Molengraaff[1] as metamorphosed rocks of the Old Permian.

5. By Wing Easton,[2] but more expressly by Volz and Tobler,[3] the "old" schists are considered as being partially Mesozoic. One may doubt, however, whether they include real mica schists.

6. Smith[4] expresses much doubt about the Archean age ascribed to the crystalline schists of the Philippine Islands, and he assigns many of them to the Tertiary.

There is thus a strong discrepancy in the opinions of these competent explorers, as the ages they assign to the schists vary from the Archean to the Tertiary. Their opinions could hardly differ more.

In order to come to a personal conclusion, I shall begin by trying to solve a few questions. First of all: Do all the series of rocks which the above-mentioned explorers have classed with the "old schists formation," really belong to it?

It would perhaps be possible to answer this question with certainty if one had gathered into a single collection all the rocks collected; but such a collection does not exist. On the contrary, those assembled by the explorers named are scattered in such a large number of museums that a comparative petrographic examination of the crystalline schists and old schists existing in the different parts of the Dutch East Indian Archipelago is absolutely impossible. One thing is certain, however, and that is that the rocks included in the "old schists formation" have been put together on a basis of negative characters, namely, their "old" appearance and the absence of fossils. It is therefore possible, perhaps very probable, that elements have been included which in fact do not belong to the old schists formation.

In order to come to a more accurate classification, it appears necessary to make, first of all, a distinction between the gneiss and crystalline schists on the one side, and the "old" schists on the other

[1] *Jaarb. Mijnwezen*, 1914. [2] *Ibid.*, 1904.

[3] *Voorl. med. over de geologie der res. Djambi*, 1912.

[4] *Handbuch der regionalem Geologie,* Philippine Islands, 1910.

side. The real gneiss must be separated from the gneissoid rocks which originated at the periphery of the younger granites at the time of their solidification. These gneissoid rocks appear in large quantity in Central Celebes, and Volz believes he has detected them in the north of Sumatra. As to the crystalline schists, it is advisable to distinguish the old mica schists from the rocks belonging to the more recent contact zones, as for instance the andalusite mica schist from Central Celebes. Finally, there is no doubt that there has been included with the "old" schists rocks[1] which do not belong to them. For instance, in his *Rapport sur les Moluques* (p. 755), Verbeek places the argillaceous schists of the island of Taliabo in the old schists formation. However, they recall so much certain schists of the Upper Cretaceous, either metamorphosed or not by the granite of the southwestern part of Central Celebes, that I can no longer consider them as being undoubtedly old schists.

Having eliminated the rocks which do not belong to them, it must be accepted that there exists in the Dutch East Indian Archipelago three series of rocks which are unquestionably of similar age, and which form the base of the other geological formations. Of these, the gneiss and mica schists are the earliest member. This double series appears as large complexes, principally in the north of Sumatra, the southeast of Borneo, on very extensive areas in Central Celebes, and in the islands of Boeroe and Ceram. As in other places, it is possible to see the lowest strata, viz., the gneiss formation, in this latter island and elsewhere in the archipelago, but especially and very clearly in Central Celebes. In its upper part, these crystalline schists seem to grade into the "old" schists, which constitute the second essential member of the oldest formations. These schists are well known in many parts of the archipelago, but only Volz has pointed out their conformability with the mica schists in the north of Sumatra.

Particularly in Central Celebes the mica schists occupy such an extensive surface, vertically as well as horizontally, that there is

[1] Tobler (and before him Wing Easton and Volz) had already called attention to this point; however, he does not exclude them systematically from the denomination "old schists."

no question of explaining them by contact metamorphism (although it is certain that such metamorphism has taken place locally). We have here to deal with regional metamorphism of ancient date. The total thickness of these schists cannot be estimated, even approximately, but it is certainly some thousands of meters. Such a thickness could not have resulted, in Celebes or in other islands of the archipelago, from the sedimentary beds of the Tertiary or of the Mesozoic. So we reach the conclusion that these rocks are pre-Mesozoic.

What is the tectonic relation between the crystalline schists of Central Celebes and those of other parts of the archipelago?

Suess[1] has remarked that Martin observed a large massif of Archean rocks in the islands Boeroe and Ceram; it consists principally of mica schists having an east-west strike. Similar rocks[2] having the same strike have been found, not only in the group of the Péling-Misool islands,[3] but also in the northwestern peninsula of New Guinea, whereas the island of Roon (east of this peninsula) is composed of gneiss. These data have led him to the hypothesis[4] that the islands Ceram and Boeroe are but the prolongation of the central mountain ranges of New Guinea, whereas the group of the Péling-Misool Islands and the northwestern peninsula of New Guinea represent the foreland of the folded land situated farther south. Suess makes of this foreland an old "massif" (Vol. III, Part 3, p. 1036). He would make a geological entity of the territory extending from Celebes to the little island Rossel, southeast of the southeastern point of New Guinea, but he writes (Vol. III, Part 3, p. 1035): "L'énorme distance qui sépare Célèbes de l'île Rossel (Louisiade), ainsi que les grandes lacunes dans nos connaissances, ne permettent pas d'énoncer ici des résultats certains." Further (Vol. III, Part 1, p. 343): "On ne peut pas dire de quelle façon la chaîne des îles orientées de l'E. à l'W. (Obi, Taliabo, etc.) se prolonge à Célèbes."

[1] *La Face de la Terre*, Vol. III, Part 1, p. 317.

[2] *Ibid.*, Vol. III, Part 3, p. 1033.

[3] *Ibid.*, Vol. III, Part 3, p. 1036: "Des terrains anciens apparaissent dans ces îles (de Taliabo à Misool), surmontés de couches mésozoiques non plissées."

[4] *La Face de la Terre*, Vol. III, Part 1, p. 318 and Vol. III, p. 1035.

As a result of the investigation made in Central Celebes, this last point is now elucidated, for the east-west strike is repeated in a very remarkable way in the schists and gneiss formations of this territory, although the older ranges of Central Celebes and Ceram have a northwest to southeast direction, owing to the post-Lutecian folding, whereas younger horsts of Central Celebes have a north-south direction, the result of more recent tectonic events. Moreover, the old massifs of Central Celebes are separated from those of the islands situated to the east of Celebes by a massif of peridotite. This latter rock has great importance in these islands.

Until the contrary is proved, the answer which one may give to the second question indicates thus that the gneiss and schists massifs, from Central Celebes to the island of Roon, are parts or horsts of an old massif which stretched formerly throughout this whole extent. Without being able to assert it dogmatically, one may say that this old massif, folded in an east-west direction, is prolonged to the west, and that it reaches the middle of Borneo, where Molengraaff and other explorers have also found tectonic entities striking almost east and west.[1]

The answers given to the first two questions are not sufficient to define precisely the age of the mica schists. This leads me to look outside the archipelago and to ask the following questions: What is the distribution of the oldest formations outside the limits of the archipelago? In what places do they reveal their age with certainty by the presence of fossils? What geo-metamorphic processes have the formations in those places undergone, and what is the relation of these processes to those which have predominated in the archipelago?

If the metamorphosing processes in other places have not been more favorable than in the archipelago for the preservation of fossils of Paleozoic, and especially of early Paleozoic age,[2] we have one reason less for presuming that fossils once existed in the schists of the archipelago.

[1] The same direction is repeated in the northern peninsula of Celebes, in the isle of Java, and in the chain of the small Sunda Islands.

[2] Neo-Carboniferous and Permian fossils have been found in the archipelago; this is a well-known fact.

To answer the foregoing questions I cannot do better than again to refer to Suess's *La Face de la Terre*.

In the eastern part of New Guinea there exist old rocks much folded and strongly upheaved,[1] which occupy the highest parts of the interior, as for instance the Owen-Stanley Range, Adolf-Haven, and the southern coast of the Huon Gulf. These rocks are also found in the north of New Caledonia, along the northeastern coast, with a direction N.20°–55°E.

If we leave New Guinea and pass to Australia, we see there the large central upland mentioned by Suess, which is composed of granite, gneiss, old schists, and a very extensive mantle of the "Desert Sandstone" (pp. 243–44). It extends to the western coast of Australia, where it is abruptly interrupted. In latitude 25°15′S. on this coast a Carboniferous series has been found (p. 243).

The eastern and southeastern parts of Australia, on the other hand, consist mostly of folded mountain ranges; there we find the Silurian, which is represented in Cape York peninsula (longitude $\pm 137\frac{1}{2}$°E., and latitude 35°S.), separating the gulfs of Spencer and St. Vincent (p. 249). North of this latter gulf, in the Flinders Range, there are outcrops of old schists and quartzites (p. 247). Further east, the old rocks of the Barrier and Grey ranges seem to be identical (p. 247); finally comes the great Australian Cordilleras, about which Suess writes (p. 248): "Des granites, des porphyres, des terrains cristallins, siluriens et dévoniens extrêmement plissés, généralement même redressés jusqu'à la verticale, constituent le noyau de la Cordillère. ... Le Carbonifère est presque horizontal."

I draw attention to the fact that in these mountain ranges the Silurian and the Devonian, although very much folded, are still recognizable by their fossils.

Let us cursorily follow Suess in his further views on the Cordilleras. With regard to Tasmania, he writes (pp. 251–52): "Du granite, des schistes cristallins et du Silurien s'y montrent redressés presque verticalement, suivant une direction méridienne; le Carbonifère, tant sous le faciès maritime que sous le faciès continental, recouvre en discordance ces terrains anciens." In the

[1] Suess, *op. cit.*, Vol. III, Part 3, pp. 1026–30.

eastern part of Victoria one meets again granite rocks and more or less vertical formations of gneiss and strata of Silurian age (p. 252). Continuing northward, we come to New South Wales, where north-south zones of granite and strongly folded Silurian and locally Devonian beds, together with old porphyry, form the eastern coast up to the Bateman Bay (latitude 35°40′S.). Northward this chain departs from the coast and disappears gradually under the horizontal Carboniferous (pp. 253–54). Further east another range consisting of granite and Silurian strata extends toward the north to Queensland (p. 254). In the northern part of New South Wales, the New England Range is composed of folded strata of Lower Paleozoic formations, with a nucleus of granite forming mountains (p. 254). To the north the granite diminishes, but the folded Devonian series increases (p. 255). To the west the Cordilleras disappears under the mantle of "desert sandstone" stretching to the Gulf of Carpentaria; at some points there rise through this mantle formations of granite and Paleozoic sediments (p. 255). Between latitude 22°30′ and 22°S. there are further patches of the Devonian and Silurian; but to the north of latitude 22°S. the coast, as far north as it is known, is formed of granite rocks, as also are the islands of the Strait of Torres, between Cape York and New Guinea (p. 256). In southeastern Australia the Silurian and Devonian, although much folded, have remained recognizable by their fossils up to latitude 22°S.

If we now pass to the opposite (northwest) side of the archipelago, to Southeastern Asia, what do we find? The islands of Banka and Billiton form a connection between the Dutch East Indies and the Malacca Peninsula. The granitic lands of these stanniferous islands extend in a northwestern direction over the southern point of the peninsula, in which (at Singapore) sandstones and old schists[1] have also been discovered. Just west of longitude 100°E. this granite chain turns to the north and ends in this direction at the island Kaw Tau, in the Gulf of Siam (Suess, Vol. III, Part 1, p. 303). To the west follows a depression in which flows the Bandon (p. 303). To the west of this depression comes another

[1] Suess, Vol. I, p. 600 and Vol. III, Part 1, p. 303. See also Verbeek, *Rapport sur les Moluques*, pp. 755–56, concerning the presence of Jurassic rocks in this series.

granite chain extending toward the north, thus forming a transition to the Birman chains (p. 303). At Tenasserim, on the neck of land east of the Mergui Islands, there are outcrops of Upper Carboniferous (p. 303) as well as of Archean rocks (I, 599). This Upper Carboniferous seems to extend far to the north in the valley of the Salwen, and at Moulmein notably (latitude $\pm 16\frac{1}{2}°$N.), in the form of limestone, it occupies a large area (p. 599). However, this eastern zone of the Birman chains, to which we have come, consists principally of Archean rocks (p. 593). To the east of Moulmein the chains extend northward and north-northeast, beyond Xieng-Sen, which is situated on the Mekong, in the northern part of Siam (Vol. III, Part 1, p. 290). Other ranges joining the former between Xieng-sen and Vien-tiane (also on the Mekong, but further down) take a northeast-southwest direction, and, decreasing in height, gradually disappear toward the southeast and the south, under the Siamese plain (p. 290). Then toward the southeast comes Siam, an immense unknown land, which, being connected with a vast area of granulite and granite, leads us to the low and old massif of Cambodge, of which we will speak later (pp. 290–91). Let us first follow the Birman chains toward the north.

According to Griesbach, the limestones of Moulmein seem to continue northward up to the highland of the Shan, where the Permian limestone is folded, the folds having been leveled (Vol. III, Part 1, p. 281). Then long ranges composed at first of crystalline schists and further north of gneiss lead north to Mandalay on the Irawaddi. And here again, in the Northern Shan States, we find once more the oldest fossiliferous strata which we had left in latitude 22°S. on the eastern coast of Australia. In fact, Suess writes (Vol. III, Part 1, p. 278): "Le chemin de fer et la route qui, de Mandalay, ont été construits vers le N.E. par Thibaw jusqu'au bac de Kunlon[1] sur la Salouen, longent sur de grandes distances la direction (N.N.E. ou E.N.E.) des roches. Les terrains les plus anciens sont à l'Ouest; au voisinage de Mandalay se montrent les couches inférieures de la série, peut-être cambriennes, puis le Silurien inférieur, le Silurien supérieur, un grès rouge pincé dans les plis,

[1] Kun-long, just to the south of the Tropic of Cancer.

et enfin la plaine récente du Salouen. ... *Le Silurien, affecté de plis, présente une 'grande variété de faciès.*"[1] The Silurian fossils of the Northern Shan States have not yet been found in the above-mentioned limestone series of the southern highland of the Shan (Vol. III, Part 1, p. 281).

From Kun-long, crossing the high ranges in a northwest direction up to Bhamo on the Irawaddi, we reach the mountains of the Siang-chan, which advance toward the north (p. 277). They consist of gneiss and crystalline schists and, for a great part, of granite (p. 277). On the west these mountains border on a zone of Carboniferous strata (p. 277). Then, turning again to the northeast, in the direction of Ta-li-fou, we recross the above-mentioned mountains of old crystalline rocks, which extend nearly to the Salwen in latitude about 25°N. Between this river and Young-tchang-fou, Lóczy found at Poupiao (latitude about 25°N.) the Silurian beds, whereas more to the east (eastward of Young-tchang-fou) he discovered Upper Carboniferous strata (pp. 276–77). This folded Paleozoic zone is situated between the Salwen and the Mekong (p. 276). East of the Mekong a broad zone of sandstone presenting the facies of the Flysch leads to the range of the Tsang-chan, consisting of crystalline schists. Next follows another sedimentary zone, composed principally of Upper Carboniferous strata which extend to the north, from Tali-fou to Batang (p. 276).

We need not continue in details our travel to the north and east, but we may limit ourselves to a few remarks. In the north the Upper Carboniferous strata play a somewhat important part, stretching themselves unconformably over older folded and denuded series of the Lower Paleozoic. After their deposition, there followed a new folding and, with regard to its tectonic history, this territory offers a fair similarity to many other countries of Eurasia (p. 276). Very far in the northeast of Central China, appear on one side the gneiss and crystalline schists, and on the other the oldest Paleozoic beds, all strongly pinched in successive mountain ranges. In the west, Silurian and Devonian series predominate (pp. 266–75); in the east, next to these, there are Cambrian strata (pp. 294–95). In Central and Northern China these formations of

[1] The italics are mine.

the Old Paleozoic attain a considerable development, as has been pointed out by von Richthofen,[1] Willis,[2] and others, as well as myself.[3] Concerning the Cambrian highland of Ordos, north of the Tsing-ling-chan, we refer also to Suess (Vol. II, pp. 303 ff., and Vol. III, Part 1, pp. 252 and 263). In that part of China unfolded Cambrian beds lie unconformably on folded and denuded Archean formations.

We need not go farther north, but now we return to Southern China, about which Suess (Vol. III, Part 1, p. 297) informs us: "Leclère[4] signale ... près de Hoaï-yuen, au Sud-Ouest de Kouen-lin, une arête de terrains précambriens et un culot de granite, accompagné, à l'Ouest, sur le Sikiang, par des roches précambriennes." And always following Suess, we proceed back again from Ta-li-fou to Cambodge, this time by the way of Yun Nan, Tonkin, and Annam. According to him (Vol. III, Part 1, p. 287), the mountain chains divide. The western ones, the Birman chains, we have followed in a zigzag way from south to north. The eastern chains lead in a southeastern direction to the Cordilleras of Annam. Without entering into details, we may say that, between Ta-li-fou and Indo-China, the oldest fossiliferous rocks continue gradually to disappear. It is only more eastward, at Lou-nan (east of Yun-nan-fou), that Leclère recognized series of the Middle and the Upper Devonian, together with various formations of the Carboniferous and the Permian (p. 296). The tectonic relation between these rocks and those of the above-mentioned pre-Cambrian (also discovered by Leclère) cannot yet be established. We read in Suess (Vol. III, Part 1, p. 297): "Les relations de ces anciens terrains ne se dégagent pas encore avec netteté des documents publiés jusqu'à présent. Il n'est guère possible de dire

[1] F. von Richthofen, *China*, 5 volumes and one atlas; Vol. I, 1877; Vol. II, 1882; Vol. IV, 1883, atlas North China, 1885; Vols. III, V; and atlas, South China, 1911.

[2] B. Willis and E. Blackwelder, *Research in China*, 2 volumes and one atlas; Vol. I, 1907.

[3] E. C. Abendanon, "La Géologie du Bassin Rouge de la province du Se-Tchouan," *Rev. Univ. des Mines*, etc., Liège, 1906. E. C. Abendanon, "Structural Geology of the Middle Yang-tzikiang Gorges," *Journal of Geology*, 1908.

[4] A. Leclère, "Etude géologique des provinces chinoises voisines du Tonkin," *Annales des Mines*, 1900–1901.

s'ils auprésentent le substratum de la plate-forme calcaire comme auprès d'I-tchang[1] ou s'ils font partie du massif ancien qui existe probablement dans la Sud-Est de la Chine, en formant un avant-pays indépendant des Altaïdes."

The most recent data about a fairly considerable area of the eastern part of the Chinese province of Yun Nan are supplied by Deprat.[2] This explorer gives many details. He writes (p. 44):

> Les terrains métamorphiques ou granitiques n'apparaissent que dans le S., dans la vallée du Fleuve Rouge. ...
>
> Le Cambrien offre un développement énorme au Yun-Nan, aussi bien dans son extension verticale qu'horizontale; *les séries fossilifères sont abondantes.*[3]
>
> J'ai découvert l'Ordovicien au N. d'Yi-léang. Le Gothlandien paraît représenté dans la même région.
>
> Le Dévonien complet offre un développement colossal au Yun-Nan. J'ai reconnu le Dévonien inférieur. Dans le Mésodovénien, l'Eifélien et le Givétien sont bien caractérisés, de même que le Frasnien et le Famennien dans le Dévonien supérieur.
>
> Nous avons pu affirmer la présence du Dinantien, représenté par plusieurs niveaux. Le Moscovien offre un développement énorme, ainsi que l'Ouralien.

About the relation between all these formations, Deprat goes into details, too, and he informs us that the structure of this territory is very complicated. According to him (pp. 251–60), a local orogenic movement (in the southeastern part of Yun Nan) took place after the Cambrian; there was uninterrupted sedimentation during the Silurian, and the corresponding beds ought to exist from Kwei-chow in the east to Burma in the west. The sedimentation continued until the Muscovian in well-developed series. Then there followed a strong ante-Uralian folding; the Uralian formation lies unconformably on the denuded folds of the Old Paleozoic. At the end of the Permian, when marine sedimentation came to an end and before any deposit of Lower Triassic sediments had taken place, a very intense orogenic movement occurred. After that, Deprat writes (p. 252): "La dernière

[1] Situated on the Yang-tzi-kiang, at the point separating the middle from the lower part of this river.

[2] J. Deprat et H. Mansuy, *Etude géologique du Yun-Nan oriental*, Vol. I, Fasc. I, 1re partie, Hanoï-Haiphong, 1912.

[3] The italics are mine.

phase principale de plissement, dont l'intensité a été véritablement très grande, est la phase de dislocation post-triasique, dont les effets ont été considérables; je la considère avec M. Lantenois comme une phase himalayenne: (p. 257) l'ensemble du Yun-Nan est alors plissé d'une façon très énergique, les charriages y prennent une amplitude très grande et la région du haut Fleuve Bleu (Yang-tsé-Kiang), prolongement sud du Yung-ling-chan, est charriée sur la région yunnannaise." The last movements were due to the upheaval which raised Yun Nan to the relatively high altitude which it occupies nowadays. They occurred during the Plio-Pleistocene.[1]

It is clear that the tectonic movements of Yun Nan, where the excessive thick Old Paleozoic series appear on such an extensive area and with a particularly great richness of fossils, have been extremely intense and numerous.

In Northern Annam, F. Deprat[2] discovered at Ben-Thuy the Ordovician, and he believes that this formation will also be discovered in Tonkin and Laos. The Devonian and Dinantian are also represented in this region, and the Uralian is once more in transgression (exactly as in Yun Nan) upon a folded and denuded territory of the older Paleozoic.

In the same way as in the Northern Shan States far to the west, here in the east of Southeastern Asia we find the most southern country where fossils of the Old Paleozoic have been discovered; for according to Suess, in the plain of Tonkin soft schists have been assigned to be Devonian; but this point is far from being sure (Vol. II, p. 277). In the island of Haï-Nan, we find Suess mentioning (Vol. III, Part 1, p. 297) that according to Madrolle, the center of the island is composed of granite and schists, and is

[1] These last movements of epirogenic character, giving rise to the phenomena of what I have called anticlinal distraction (in a booklet titled *Die Grossfalten der Erdrinde*, Leyde, Holland, 1914), which phenomena led to the forming of important tectonic depressions, are so completely similar to those of the Plio-Pleistocene period in Central Celebes, where I have classified them together in a single process of grand-folding, that I do not hesitate to identify the most recent epirogenic movements of Yun Nan with those of Central Celebes, the latter having induced the upheaval of this country to its present high altitude.

[2] "Sur la découverte de l'Ordovicien, à Trinucleus, et du Dinantien dans le Nord-Annam, etc.," *Comp. Rend. Ac. d. Sc.*, 28-5-12, T. 154, pp. 1452-54.

surrounded by a sandy argillaceous formation of red color in the north and yellow in the east.

Patches of Carboniferous limestone occur more abundantly as we approach the Cordilleras of Annam, on the east coast. Suess mentions (Vol. III, Part 1, p. 297) that Bell crossed these Cordilleras in a westerly direction, starting from Tourane (on the eastern coast of Annam, by latitude 16°10′N.). They appear to be composed of various zones, first of dioritic and granitic rocks, then of gneiss and crystalline schists, and lastly of rather recent formations (Vol. II, p. 275, and Vol. III, Part 1, p. 297). The granitic rocks advance toward the south, along the coast, from latitude 14°N. to Cape St. Jacques, southeast of Saigon, and they must be the southern extremity of a very long mountain chain stretching in a northern direction to the granite highland of Laos (Vol. II, p. 275).

In this way we come back to the old low massif of Cambodge and to the delta of the Mekong, in Cochin-China.

Like Australia to the southeast, Cochin-China and Tonkin constitute very old uplands (Suess, Vol. I, p. 607) to the northwest of the East Indian Archipelago. Between these uplands we have the granite massifs of southwest Borneo, which separate the folds of the eastern part of this island into two zones, one extending toward the west and the other toward the south, the massifs of granite, gneiss, and crystalline schists of Central Celebes and the horsts of Boeroe and Ceram which, together with others, are probably part of an old massif (Suess, Vol. III, Part 3, p. 1036).

It is only southward from latitude 22°S., along the eastern coast of Australia on one side, and northward from the Shan states, North Annam, and Yun Nan on the other side, that the Silurian and Devonian appear. Then, on the northern side, more to the north, exists the Cambrian and the pre-Cambrian beneath. The latter plays an important part to the south, but still more north of the Tsing-ling-chan in China. On the southern side (viz., in Australia), however, these last-mentioned two formations do not appear.

In the intermediate territory, to which the archipelago belongs, outcrops of old crystalline schists occur in many places, but no explorer has discovered any fossils of the Old Paleozoic.

The Old Paleozoic series which border the periphery of the above-mentioned territory are strongly folded. The geo-metamorphic processes in those areas, that are nevertheless characterized by their fossils, have certainly not been less powerful than in the intermediate territory stretching from latitude 20°N. to latitude 22°S., over the southeastern part of Asia, the Dutch East Indian Archipelago, New Guinea, and part of Australia.

Is it then credible that in this extensive territory, the extent of which from southwest to northeast is not known, all fossils of the Old Paleozoic should have disappeared? What particular reasons not valid for Southeastern Asia and Eastern and Southeastern Australia, could plausibly explain their disappearance? Is it not more logical to consider, under these circumstances, the absence of fossils, not as an indirect proof, but as a powerful argument for the hypothesis that in the above-outlined territory there never existed any Old Paleozoic fossils?

Is it not in the same way remarkable that the same transgression of the Upper Carboniferous and the Permain over the folded and denuded folds of the Old Paleozoic, which has been observed as well in Southeastern Asia as in Eastern Australia, is also apparent in some parts of the intermediate territory (for instance, in the west of Sumatra and in the island of Timor), whereas fossils of the Old Paleozoic have nevertheless not been found there?

From the above-stated considerations it seems not only possible to deduce a precise conclusion about the age of the crystalline schists formation, but also to deduce others of essential interest. They are the following:

1. The gneiss, the mica schists, the phyllites, and the real "old" schists (thus with the omission of the rocks which do not make part of them) must be Archean and pre-Cambrian rocks.

2. They once built up an Old Paleozoic continent, which extended at least over an area of 45° in latitude, between the tropics, from the southeast of Asia to the east of Australia. Its development from southwest to northeast is unknown, owing to the presence of the Indian and Pacific oceans, but at all events this continent must have included most of Sumatra on the southeast, and the Philippine Islands on the northeast, considering that, in

those countries too, there has not yet been found any fossil of the Old Paleozoic. To the west, it may have stretched out as far as Madagascar.

3. In the central part, north and south of the equator, mountain ranges of an almost east-west direction must have played an important part in this very old continent.

4. The Cambrian deposits on the north leaned against it, but in the south they have not been found. Nevertheless they may have existed south of Australia, where the ocean now is.

5. In the north, to a large extent toward the south, and in the south, fairly far toward the north, a transgression passed over the border areas of this continent during the Silurian, the Devonian, and the Lower Carboniferous periods (with a secondary unconformability).

6. Then a folding occurred of these sediments of the Old Paleozoic. Border ranges were formed at the periphery of the old continent which, from a tectonic point of view, are similar to the Tertiary Cordilleras.

7. During the Middle Carboniferous, denudation and leveling took place.

8. Lastly, the transgressions of the Upper Carboniferous and the Lower Permian seas invaded (with a real unconformability), not only the denuded Eopaleozoic border ranges, but also part of the old continent itself.

To this continent, the existence of which during the Old Paleozoic seems to be evident, I give the name of *Aequinoctia*.

It was during the Permo-Carboniferous that its dislocation began, in the territory of the Dutch East Indian Archipelago. The demembration of this oldest continent must have continued during the Mesozoic and the Tertiary; and so it became, in time, one of the most unsteady parts of the earth's crust. In this connection it is interesting to observe that the territory of the archipelago exhibits nowhere the tremendous development of the Mesozoic which has been observed, for instance, in the Alps, though uninterrupted sedimentation has taken place in some regions during the whole Mesozoic and part of the Tertiary. As a rule, however, complete series appear hardly anywhere. This

peculiarity can best be explained, I venture to suggest, by the aforesaid demembration of the original old territory.

A last question before concluding: Is it probable, in the future, that there may still be discovered in this territory fossils of the Old Paleozoic? Will it be the same with *Aequinoctia* as with the Jurassic Sino-Australian continent of Neumayr?

The numerous explorers who have worked in so many different parts of this region, still so unknown in the time of Neumayr, have succeeded in the course of years in making known, as we have seen, in a fairly continuous series, every period from the Upper Carboniferous to the Recent. Older fossils have not as yet been discovered, notwithstanding the greatest efforts and the closest attention, and in spite of the fact that the rocks preceding the Upper Carboniferous outcrop in large areas and are frequently deeply cut by erosion, thus offering very favorable points of investigation. Under these circumstances, I suppose that the hypothesis of the existence of *Aequinoctia* during the Old Paleozoic may be maintained.

ON COARSE GABBROID DIABASE IN WESTFIELD, MASSACHUSETTS[1]

EARL V. SHANNON
United States National Museum

In the western part of the town of Westfield, Massachusetts, a number of quarries have been opened in the Holyoke diabase sheet. These quarries are the same which have furnished the beautiful datolite specimens which are to be found in all collections. The diabase or trap in which these quarries are located is the middle or main extrusive trap sheet of the Connecticut Valley Triassic area. Here the main portion of the sheet is composed of a gray holocrystalline diabase of fine to medium grain not unlike the intrusive traps which form East and West Rocks near New Haven. In the northernmost of the four quarries there occur, included in the normal rock, irregular areas of a gabbroid rock very unusual in appearance for an extrusive lava. While studying the occurrence of datolite and other secondary minerals in these quarries, the writer's attention was attracted to these very coarse-grained phases of the sheet and they were examined in some detail. At first it was believed that they represented a later intrusion which had chanced to penetrate the previously existing flow, but a study of the relations of the coarse material to the surrounding diabase of normal grain led to the abandonment of this view. The contact with the surrounding rock is sharp, the transition from coarse to fine material being accomplished in a distance of an inch or less. The coarse-grained gabbro forms irregular rounded areas often many yards in diameter in the finer-grained diabase. In the hand specimen this coarse rock shows broad blades of bronzy greenish-black pyroxene which reach an inch or more in length, imbedded in a coarse granular aggregate of pyroxene and greenish feldspar. Under the microscope the rock is seen to be composed of large

[1] Published by permission of the Secretary of the Smithsonian Institution.

crystals of pyroxene and plagioclase in a subordinate fine-grained ground-mass composed largely of needle-like crystals of plagioclase with interstitial augite in anhedral patches now largely altered to a greenish-brown chlorite which is probably diabantite.[1] The large pyroxene phenocrysts are rather pale greenish-brown in color, with well-developed cleavage. They are unaltered and are in part transparent and in part turbid from the presence of an opaque brownish pigment. They are not commonly simple but are bladed aggregates made up of a number of irregular interlocking crystals not quite in parallel position so that they do not all extinguish simultaneously. In composition this pyroxene is ordinary augite. The plagioclase phenocrysts are characterized by rather narrow twinning lamellae and are near-basic andesine in composition. The most striking microscopic feature of the rock is the presence of broad patches of a graphic intergrowth of plagioclase and augite in fixed orientation, giving remarkable pegmatitic textures entirely analogous to the quartz-feldspar aggregates of graphic granite. In places a phenocryst of plagioclase terminates in a branching fernlike intergrowth of plagioclase and augite.

A question naturally arises as to the origin of such coarse forms in an intrusive flow less than a hundred feet in thickness. Ordinarily such surface flows cool too rapidly to permit the growth of large crystal individuals. The mode of occurrence of this coarse phase indicates that the large crystals of plagioclase and augite were formed after the lava had reached its present position and precludes the supposition that it was intruded into the extrusive sheet after the sheet had been buried by later sedimentation. Emerson[2] has described similar coarse forms from this trap sheet further north associated with mudstone, pitchstone, etc., formed by the molten lava coming in contact with water and mud. Strangely enough, he attributes the coarseness of grain of the plumose diabase to sudden cooling or quenching of the molten

[1] Earl V. Shannon, "Diabantite, Stilpnomelane, and Chalcodite from Westfield, Massachusetts," *Proc. U.S. Nat. Mus.* In print.

[2] B. K. Emerson, "Plumose Diabase and Palognite from the Holyoke Trap Sheet," *Bull. Geol. Soc. Amer.*, XVI (1905), 91.

material by the water. This is quite contrary to our knowledge of the effect of the rate of cooling upon the grain of igneous rocks. The writer after some study has reached the conclusion that the coarseness of crystallization of the gabbroid diabase is due to absorption of confined water by the still molten portion of the flow, with the formation of miniature pegmatite chambers. Quite certainly here as elsewhere the lava of this flow encountered moist mud flats and ponds of water. The coarse gabbro occurs for the most part near but not at the top of the flow. If we may conceive the top of the flow as forming here a resistant crust due to early solidification, the water from below heated to a high temperature and ascending through the still molten lava must come to rest beneath the previously solidified crust and might readily be conceived to mix with the still molten material to form a magma rich in volatile constituents and thus capable of remaining fluid for longer periods and at lower temperatures than when in its original dry state. This would permit the formation of coarse-grained pegmatitic textures like those here described. Emerson has shown in the paper cited that water did ascend through the flow and that such water in some instances caused explosions rupturing the upper crust. It is easy to understand how pressures could obtain in a pegmatitic chamber of the sort indicated sufficient to rupture the roof of solid diabase after the formation of large plumose crystals of augite was well advanced. The remaining molten material would be chilled following the explosion and yield perlitic glasses associated with plumose diabases exactly in the manner described by Emerson.

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VOLUME XXVII NUMBER 8

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

EDITED BY

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NOVEMBER-DECEMBER 1919

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, LONDON
THE MARUZEN-KABUSHIKI-KAISHA, TOKYO, OSAKA, KYOTO, FUKUOKA SENDAI
THE MISSION BOOK COMPANY, SHANGHAI

November-December 1919 Vol. XXVII, No. 8

THE JOURNAL OF GEOLOGY

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15. ¶ The subscription price is $4.00 per year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶ Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $4.30), on single copies 4 cents (total 69 cents); for all other countries in the Postal Union, 53 cents on annual subscriptions (total $4.53), on single copies 11 cents (total 76 cents). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

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Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editors of THE JOURNAL OF GEOLOGY, the University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Separates, if desired, must be ordered in advance of publication. Separates of leading articles will be printed as ordered, of which 50 (without covers) will be furnished *gratis*, the actual cost of the remainder (and covers, if desired) to be paid for by the author. The actual cost may vary, and will depend upon the amount of work in remaking the pages into forms, presswork, paper, binding, etc. Separates containing half-tones may be expected to cost somewhat more, the increase depending upon the number of cuts and the amount of work required upon them.

Entered as second-class matter, March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

VOLUME XXVII NUMBER 8

THE

JOURNAL OF GEOLOGY

NOVEMBER-DECEMBER 1919

THE RIGIDITY OF THE EARTH

A. A. MICHELSON AND HENRY G. GALE

In 1914, in the March number of the *Astrophysical Journal* (**39**, 105, 1914), an account was published of a preliminary experiment to determine the rigidity of the earth. At that time it was announced that the experiment would be repeated, using an interference method. The new arrangements were completed and a new series of observations begun on November 20, 1916, and continued until November 20, 1917. The reduction of the observations was interrupted by the war in the summer of 1917 and could not be resumed until April 1919.

The same pits and pipes on the grounds of the Yerkes Observatory at Williams Bay, Wisconsin, were used as in the preliminary experiment. In that experiment pipes 502 feet long and 6 inches in diameter were placed 6 feet underground. One pipe was laid accurately N–S and the other E–W. The pipes ended in pits 10 feet deep and 8 feet square, walled with concrete. The pipes were carefully leveled, and half filled with water, so that an air space extended from end to end of each pipe, above the water. The pipes ended in air-tight gauges provided with windows through which the changes in water-level could be determined by measuring with microscopes the distance between pointers just below the surface of the water and their totally reflected images.

In the present experiment interferometers replaced the microscopes and pointers. The arrangement of the interferometers, one at each end of each pipe, is shown in Figure 1. The compensating glass serves to seal the pipe. The lower mirror is movable vertically and has also the usual adjustments for regulating the width and orientation of the fringes. The film of water over this mirror is kept thin, usually about 0.5 mm, as the viscosity of the water

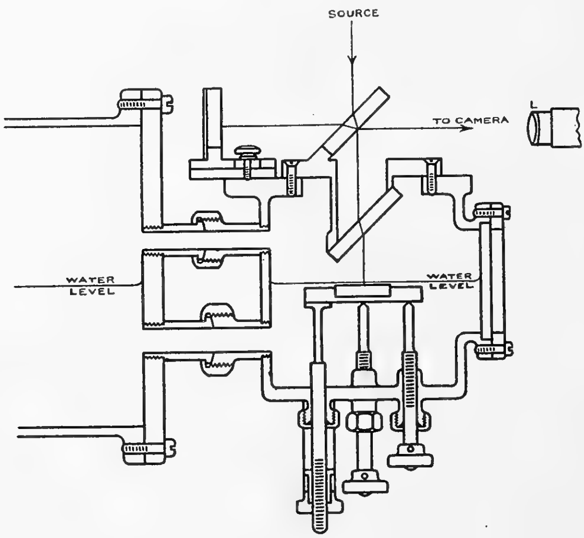


FIG. 1

helps to dampen ripples and minor disturbances. The changing thickness of the water film, due to the tides, caused the shift of fringes. The arrangement for recording the fringes was as follows: Horizontal fringes were projected by the lens L on a narrow vertical slit about 0.2 mm in width. Clockwork drew a moving-picture film behind this slit at the rate of about 2 cm per hour. In order to prevent the condensation of moisture on the optical parts the end of the pipe, interferometer, and camera were all inclosed in a galvanized iron box, in which large trays of calcium chloride were kept. An incandescent light was continually burning near the interferometer to keep the temperature slightly raised.

Other interference arrangements are obvious which would give a displacement of a greater number of fringes, or permit the use of a shorter pipe; e.g., the fringes formed between the water surface and the lower mirror might be used, or the lower mirror might be dispensed with and use made of the fringes formed by the light reflected from the water surface and the vertical mirror. But the arrangement actually used was the most satisfactory, since the long pipes, 502 feet, were already installed.

The sources of light were commercial alternating-current Cooper-Hewitt mercury lamps. They proved very reliable and satisfactory. By using as filters thin films of a saturated solution of esculin in water, all wave-lengths from the arc shorter than λ 4358 were absorbed, and the positive film used was not sensitive to the longer wave-lengths. The exposed portions of the films were removed and developed each week. The light was abundantly strong for satisfactory negatives, and it was possible to use 1.5 mm diaphragms on the projecting lenses. This gave sufficient sharpness to the fringes, even when there was a considerable change in their focus. It was necessary to readjust and refocus the fringes in only one pit during the entire year, although the width of the fringes was altered once or twice in two other pits. One of the mirrors required resilvering. One of the pits ran throughout the year without readjustment of the fringes or camera. The pits and cameras were in charge of Mr. George Monk and Mr. Frank Sullivan, of the Yerkes Observatory staff.

A relay which moved a shutter in front of the projecting lens was placed in each pit. The four relays were connected in series with a clock in the observatory, so that the time could be conveniently and accurately controlled. Once an hour the clock made contact, and a storage-battery circuit was closed through the relays and the light was cut off by the shutters for about 20 seconds. Very accurate time-marks were secured in this way. The control clock was kept six minutes faster than Central Standard Time in order to simplify the computations and bring the observations into agreement with them. (The longitude of Yerkes Observatory from Greenwich is $5^h\ 54^m\ 13^s$.)

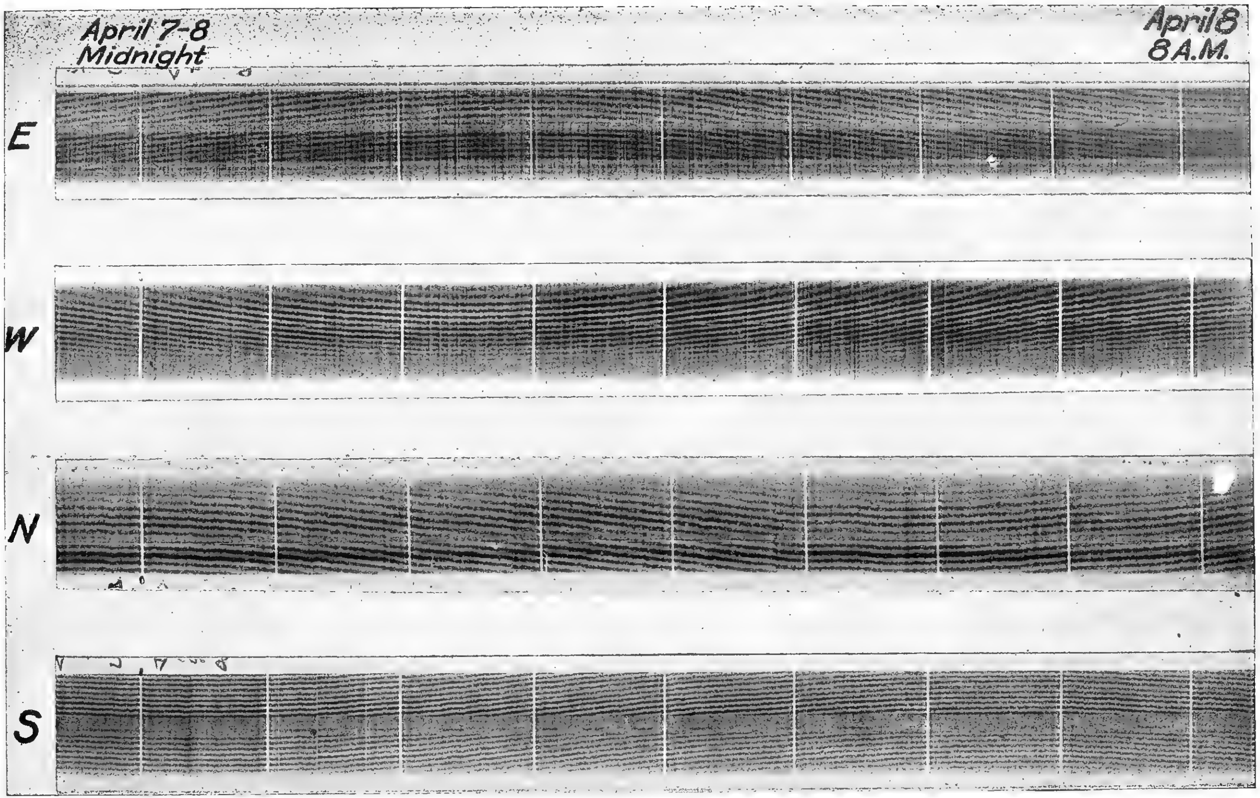
The films were measured by sliding them on a lathe-bed beneath a low-powered microscope. The fringes, estimated to tenths, were counted as they moved up and down, and the numbers recorded for each hour. The difference in the motion at the two ends of each pipe gave the numbers for plotting the observed tides.

The calculated tides were drawn from the computed shift in fringes, the calculations being made for two-hour intervals. The calculations were made under the direction of Professor F. R. Moulton by Mr. Albert Barnett and Mr. Horace Olsen. The formulae are given in the accompanying article by Professor Moulton, "Theory of Tides in Pipes on a Rigid Earth." The value of μ for the water used was found to be 1.3408 for λ 4358, and this is probably correct to within considerably less than 0.1 per cent for the range of temperatures used.

Calculated and observed curves for the period from March 24 to April 21, 1917, are reproduced in Figures 2 and 3. The dotted curve represents the observed and the full curve (displaced vertically to avoid overlapping) 0.7 of the calculated values of the tides. The ordinates are numbers of fringes, $N=\frac{2(\mu-1)d}{\lambda}$, and one fringe corresponds to 1/1564 mm.

The observed and calculated curves were plotted on long rolls of co-ordinate paper to the following scale: abscissae, 1 cm = 1 hour; ordinates, 1 cm = 2 fringes. In order to have the amplitudes approximately equal, 0.7 of the calculated values were plotted instead of the full amplitudes. Beginning with 10:00 A.M. November 20, 1916, the curves, both observed and calculated, were divided into periods of $12^{h}42$ for the semi-diurnal and $25^{h}82$ for the diurnal lunar tides. The principal solar tide, period twelve hours, was started at noon of the same day. In order to avoid a cumulative error in the case of the semi-diurnal lunar tide the period $12^{h}4206013$ was put on a computing machine and added repeatedly to the initial time to get the exact beginning of each new period throughout the year. This process was repeated, using the period $25^{h}8193409$ for the diurnal lunar tide.

The observations were reduced in groups of about a lunar month each, by dividing each period into ten equal parts (twelve



PHOTOGRAPHIC RECORDS TAKEN SIMULTANEOUSLY

in the case of the solar tide), and taking the mean of the first, second, third, etc., ordinates. The resulting values were plotted and any error in computation was usually indicated by the failure of a point to fall on a smooth curve. It is important to treat the observed and calculated tides both in the same way, as any distortion in the resulting sine curves due to lack of complete elimination of other periods affects the two alike. This is, of course, most noticeable in the case of the diurnal tide on account of its smaller amplitude and the smaller number of periods. Mr. Fred Pearson gave valuable assistance in measuring the films, in plotting the curves, and in deducing the various tides from the curves.

Very little trouble was caused by sudden erratic changes in the fringes. Occasionally, however, earthquakes would cause the fringes to disappear for from ten minutes to half an hour. Once the effects of an earthquake were evident for about six hours. During three hours of this time the fringes were completely obliterated.

The most serious disturbance was a gradual change in the slope of the observed curves. This would often be fairly uniform and gradual for a month or two. At some times the curves would rise and at others fall. Sometimes the N–S and E–W slopes had the same sign, and sometimes opposite signs. We have been able to discover nothing systematic about this drifting. It may have been caused by unequal settling at the ends of the pipes, by temperature changes in the pits, or by tilting in the earth's strata. There were always large shifts of the fringes when the lights came on after having been interrupted by the power company for a half-hour or so. The change of slope was eliminated in reducing each monthly tide, as given in Tables I–VI, and the tide for the whole year, opposite Y in the tables, by distributing the change of level uniformly throughout the period. This change of slope is quite conspicuous in Figure 3, where the observed E–W tide showed a fairly uniform and distinct downward trend throughout nearly the whole month. The change in slope of the N–S curves for the same period is comparatively small, as shown in Figure 2.

Plate III is from four photographs taken simultaneously in the four pits. The reproductions are positives on the same scale

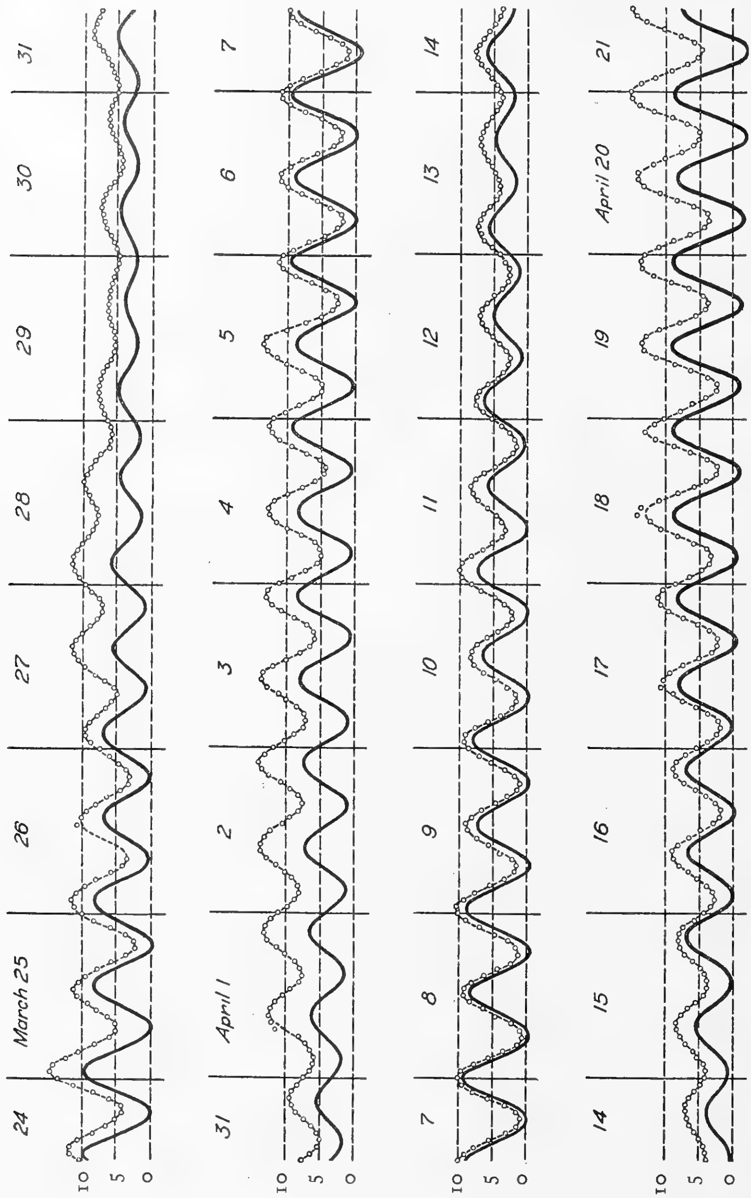


FIG. 2.—N–S tides, March 24 to April 21, 1917. Dotted curves, observed values. Full curves, 0.7 of calculated values

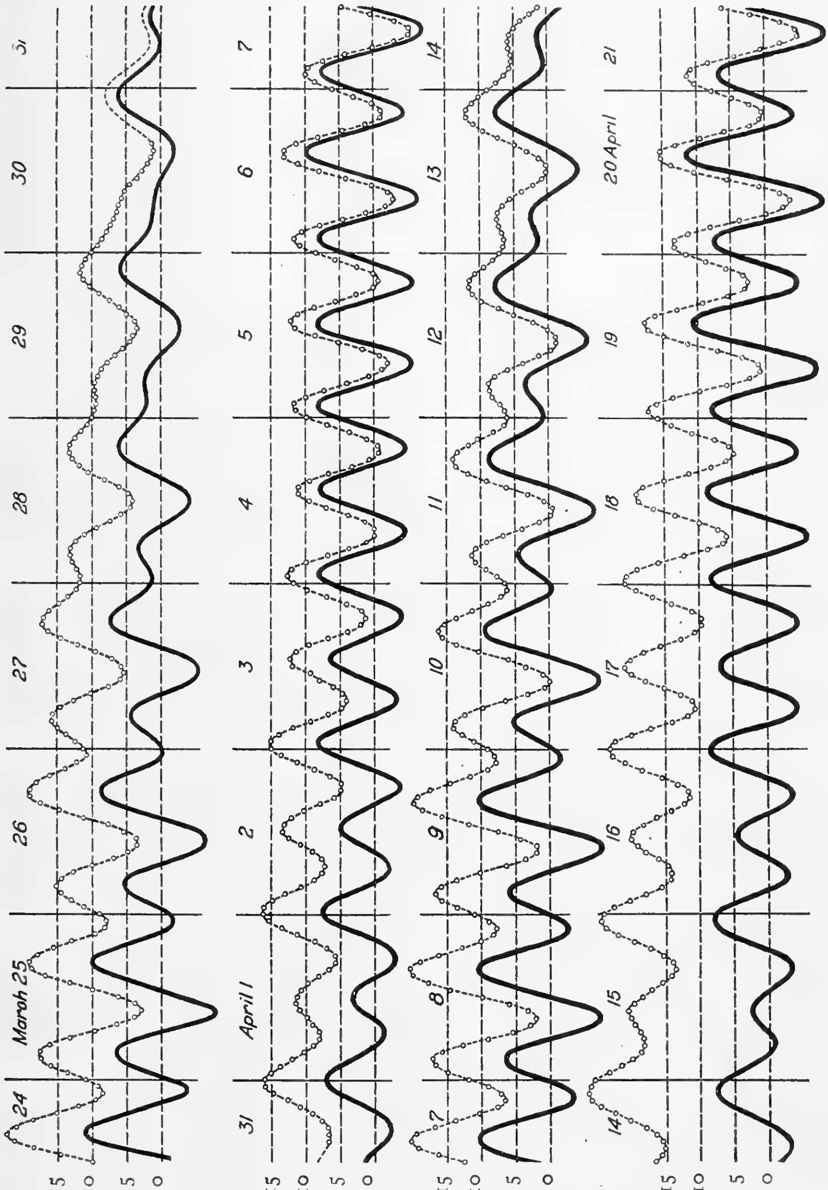


FIG. 3.—E–W tides, March 24 to April 21, 1917. Dotted curves, observed values. Full curves, 0.7 of calculated values

as the originals, and represent fairly well the average quality of the films.

A graphical solution is excellent for detecting erroneous points and serves well to give the ratio of the observed to the calculated amplitude, but for determining the phase-difference of the two curves it is not so satisfactory. A least-squares method was therefore used to secure the ratio of amplitudes, R, and the displacement in phase $\Delta\phi$ of the observed with respect to the calculated tide. The following example illustrates the method of reduction. It is for the semi-diurnal tide, first month, E–W. For convenience the solar periods were divided into twelve parts instead of ten, but in other respects the method of reduction is the same.

In Tables I–VI the numbers in the columns under M denote the different approximate lunar months; under N is given the number of periods used. For the solar tides missing portions of the observed curves were sketched in, following the computed tides, thus giving a total of 730 periods for the year, but for the semi-

FIRST MONTH, SEMI-DIURNAL, E–W OBSERVED

θ	y	Sin θ	y Sin θ	Cos θ	y Cos θ
0°	17.58	0.0000	0.0000	1.0000	17.5800
36	18.74	.5878	11.0153	0.8090	15.1606
72	15.73	.9511	14.9608	.3090	4.8605
108	10.46	.9511	9.9485	− .3090	−3.2321
144	4.83	.5878	2.8390	− .8090	−3.9074
180	0.60	.0000	0.0000	−1.0000	−0.6000
216	−0.20	−.5878	0.1234	−0.8090	0.1698
252	2.58	−.9511	−2.4538	− .3090	−0.7972
288	7.76	−.9511	−7.3805	.3090	2.3978
324	13.48	−.5878	−7.9235	.8090	10.9053
Total			+21.1292		+42.5373

$$\alpha=\frac{21.1292}{5}=+4.2258 \quad \beta=\frac{42.5373}{5}=+8.5075$$

$$\tan\phi_c=\frac{\beta}{\alpha}=2.0132$$

$$\phi_c=63°35'$$

$$c=\sqrt{\alpha^2+\beta^2}$$

$$c=\sqrt{90.2350}$$

$$c=9.499$$

$$y=9.499\sin(\theta+63°35')$$

FIRST MONTH, SEMI-DIURNAL, E–W CALCULATED

θ	y	Sin θ	y Sin θ	Cos θ	y Cos θ
0°	17.38	0.0000	0.0000	1.0000	17.3800
36	18.89	.5878	11.1035	0.8090	15.2820
72	16.73	.9511	15.9119	.3090	5.1695
108	11.58	.9511	11.0137	− .3090	−3.5782
144	6.13	.5878	3.6032	− .8090	−4.9591
180	0.90	.0000	.0000	−1.0000	−0.9000
216	0.00	−.5878	.0000	−0.8090	.0000
252	2.23	−.9511	−2.1209	− .3090	− .6890
288	7.16	−.9511	−6.8098	.3090	2.2124
324	12.91	−.5878	−7.5885	.8090	10.4441
Total	....	....	+25.1131	....	+40.3617

$$\alpha=\frac{25.1131}{5}=+5.0226 \quad \beta=\frac{40.3617}{5}=+8.0723$$

$$\tan\phi_d=\frac{\beta}{\alpha}=+1.6072$$

$$\phi_d=58°7'$$

$$d=\sqrt{\alpha^2+\beta^2}$$

$$d=\sqrt{90.3885}$$

$$d=9.507$$

$$y=9.507 \sin(\theta+58°7')$$

$$R=\frac{c}{d}\frac{0.7\times 9.499}{9.507}=0.699 \qquad \Delta\phi=\phi_c-\phi_d=+5°28'$$

diurnal and diurnal lunar tides only such portions of the observed curves were used as gave complete periods. Under a and c are given the amplitudes and under ϕ_a and ϕ_c the phase constants for the observed curves and under b and d and ϕ_b and ϕ_d the corresponding quantities for the calculated curves. In taking the means the value for each month is weighted in proportion to the number of periods in the month. Below the mean R and $\Delta\phi$ in each case is given the average difference from the mean. At the bottom of each table opposite Y are given the results obtained by computing the tides for the entire year as a single period instead of for a month at a time. The results agree closely with the means for the thirteen months, and are shown graphically in Figures 4 to 8.

Violent storms broke down the electric wires during February and March on several occasions, interrupting the electric current for a few hours. The pits cooled, and there were resulting large

shifts of the fringes after the current was re-established. It seems highly probable that the large difference of phase which is shown for the fourth month E–W diurnal tide is due to such disturbances.

TABLE I

N–S, Semi-Diurnal, Lunar

M	N	a	b	ϕ_a	ϕ_b	R	$\Delta\phi$
1......	60	6.217	6.373	149°14′	147°48′	0.683	1°26′
2......	54	5.703	6.489	147 53	144 4	.615	3 49
3......	48	7.261	6.780	146 15	145 56	.750	0 19
4......	45	6.750	6.739	148 44	146 23	.701	2 7
5......	55	6.041	6.269	148 37	148 54	.675	−0 17
6......	54	6.426	6.551	148 35	147 57	.687	0 38
7......	54	6.332	6.344	148 40	145 56	.699	2 44
8......	51	6.052	6.344	147 47	146 58	.668	0 49
9......	55	6.036	6.319	146 36	147 16	.669	−0 40
10......	54	5.821	6.210	149 27	147 32	.656	1 55
11......	54	5.875	6.140	148 14	148 16	.670	−0 2
12......	55	6.027	6.284	149 18	147 46	.671	1 32
13......	45	6.330	6.515	152 39	150 36	0.680	2 3
Av....	....	6.203	....	....	....	{ 0.678 { ±.019	1°15′ ±1 2
Y	684	6.173	6.401	148°24′	147°32′	0.675	0 52

TABLE II

E–W, Semi-Diurnal, Lunar

M	N	c	d	ϕ_c	ϕ_d	R	$\Delta\phi$
1......	60	9.499	9.507	63°35′	58° 7′	0.699	5°28′
2......	54	8.908	9.096	64 40	58 5	.686	6 35
3......	48	9.899	10.075	61 28	55 47	.688	5 41
4......	43	10.220	10.369	69 46	65 2	.690	4 44
5......	56	9.131	9.380	63 43	57 0	.681	6 43
6......	53	9.660	9.667	65 4	57 54	.700	7 10
7......	54	9.496	9.632	64 26	57 6	.690	7 20
8......	51	9.445	9.331	60 48	55 4	.709	5 44
9......	55	9.206	9.316	63 24	57 30	.692	5 54
10......	54	8.773	9.095	64 52	56 32	.675	8 20
11......	54	8.982	9.108	61 31	57 18	.690	4 13
12......	55	9.138	9.337	63 12	58 12	.685	5 0
13......	45	9.809	9.747	67 20	61 44	0.704	5 36
Av....	....	9.373	....	....	....	{ 0.691 { ±.007	6° 4′ ± 55
Y	682	9.380	9.485	63°56′	58°10′	0.692	5 46

Moreover, this month, on account of the interruptions, contained but 20 periods instead of the usual 26. The mean is therefore given for twelve lunar months, omitting the fourth, on the line Av_{12} as

TABLE III

N–S SOLAR

M	N	a	b	ϕa	ϕb	R	$\Delta\phi$
1......	56	2.554	2.628	104° 8′	99°39′	0.680	4°29′
2......	62	2.392	2.294	100 13	85 45	.730	14 28
3......	48	4.883	4.272	93 34	82 59	.800	10 35
4......	70	2.778	3.132	88 41	80 35	.621	8 6
5......	58	3.840	3.744	100 26	97 14	.718	3 12
6......	54	3.595	3.485	102 43	99 59	.722	2 43
7......	56	2.818	2.570	109 29	103 27	.768	6 2
8......	54	2.513	2.312	109 1	99 49	.761	9 12
9......	56	2.771	2.506	87 23	84 18	.774	3 5
10......	56	2.944	3.108	89 35	86 54	.663	2 41
11......	56	3.562	3.456	99 10	95 51	.721	3 19
12......	56	3.154	3.291	108 6	103 40	.671	4 26
13......	48	3.775	3.889	98 55	99 38	0.679	−0 43
Av....	....	3.161	....	....	....	{ 0.714 ± .041	5°38′ ±3 16
Y....	730	3.140	3.063	99°25′	93°20′	0.718	6 5

TABLE IV

E–W SOLAR

M	N	c	d	ϕc	ϕd	R	$\Delta\phi$
1......	56	3.641	3.838	13°54′	9°40′	0.664	4°14′
2......	62	3.218	3.400	3 31	355 40	.663	7 51
3......	48	6.172	6.488	358 28	352 59	.666	5 29
4......	70	4.444	4.665	354 5	350 14	.667	3 51
5......	58	5.534	5.480	11 19	6 33	.707	4 46
6......	54	5.104	5.173	16 52	10 59	.691	5 53
7......	56	3.687	3.731	21 32	13 53	.692	7 39
8......	54	3.487	3.407	15 3	8 22	.716	6 41
9......	56	3.450	3.689	359 50	353 28	.655	6 22
10......	56	4.371	4.595	3 14	356 36	.666	6 38
11......	56	5.045	4.993	7 57	4 32	.707	3 25
12......	56	4.689	4.858	16 28	14 16	.676	2 12
13......	48	5.621	5.626	10 0	6 11	0.699	3 49
Av....	....	4.459	....	....	....	{ 0.681 ± .018	5°19′ ±1 28
Y....	730	4.399	4.522	8° 6′	2°23′	0.681	5 43

TABLE V

N–S, Diurnal, Lunar

M	N	a	b	ϕ_a	ϕ_b	R	$\Delta\phi$
1......	26	0.962	0.551	185°35′	193°24′	1.222	− 7°29′
2......	28	0.653	.470	189 59	188 19	0.973	1 40
3......	24	1.306	.550	319 49	201 31	1.662	118 18
4......	20	2.042	.701	305 43	218 48	2.039	86 55
5......	25	0.117	.509	189 00	203 36	0.336	−14 36
6......	26	.347	.465	218 59	197 7	.522	21 52
7......	26	.335	.499	190 27	194 25	.475	− 3 58
8......	25	.279	.484	193 22	193 25	.404	− 0 3
9......	26	.297	.463	213 32	195 58	.451	17 34
10......	26	.538	.473	154 44	193 31	.796	−38 37
11......	26	.277	.455	164 41	194 4	.426	−29 23
12......	26	.282	.365	214 36	188 58	.541	+25 38
13......	22	0.359	0.480	181 1	191 58	0.523	−10 57
Av_{13}...	....	0.574	....	....	....	0.777 ±0.411	11°57′ ±30 49
Av_{12}...	....	0.478	....	....	....	0.694 ±0.313	7 3 ±26 6
Av_{11} ..	....	0.408	....	....	....	.612 ±0.216	− 2 25 ±16 12
Y_{13} ...	326	0.281	0.503	229°23′	197°57′	0.411	31 26
Y_{12} ...	306	0.298	0.492	203 24	196 07	.424	7 17
Y_{11} ...	282	0.411	0.489	188 14	196 56	0.588	− 8 42

TABLE VI

E–W, Diurnal, Lunar

M	N	c	d	ϕ_c	ϕ_d	R	$\Delta\phi$
1......	26	4.107	3.819	282° 9′	284°56′	0.753	−2°47′
2......	28	3.845	3.725	275 48	278 19	.723	−2 31
3......	24	4.164	4.193	288 57	288 58	.695	−0 1
4......	20	3.525	3.603	317 6	293 57	.685	23 9
5......	25	3.925	4.134	287 31	285 43	.665	1 48
6......	26	3.517	3.850	291 19	288 14	.639	3 5
7......	26	3.925	3.900	281 44	285 13	.704	−3 29
8......	25	4.032	3.968	281 54	281 24	.711	0 30
9......	26	3.710	3.518	286 41	283 20	.738	3 21
10......	26	3.480	3.595	282 29	284 21	.678	−1 53
11......	26	3.383	3.442	281 40	283 59	.688	−2 19
12......	26	3.439	3.470	278 57	281 36	.694	−2 39
13......	22	4.526	4.485	275 17	280 35	0.706	−5 18
Av_{13}...	326	3.807	....	....	....	0.699 ±0.022	0°29′ ±4 11
Av_{12} ..	306	3.825	....	....	....	0.700 ±0.024	−1 0 ±2 8
Y_{13} ...	326	3.759	3.799	284°55′	283°22′	0.693	1 33
Y_{12}...	306	3.807	3.815	283 52	282 43	0.699	1 9

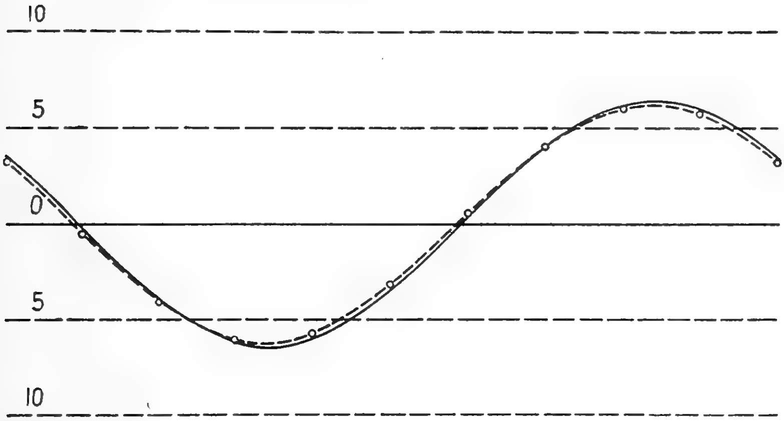


FIG. 4.—N–S semi-diurnal lunar tide for entire year. Dotted curve from observed values

$$y=6.173 \sin(\theta+148^\circ 24')$$

Full curve from 0.7 calculated values

$$y=6.401 \sin(\theta+147^\circ 32')$$
$$R=0.7 \quad a/b=0.675. \quad \Delta\phi=52'$$

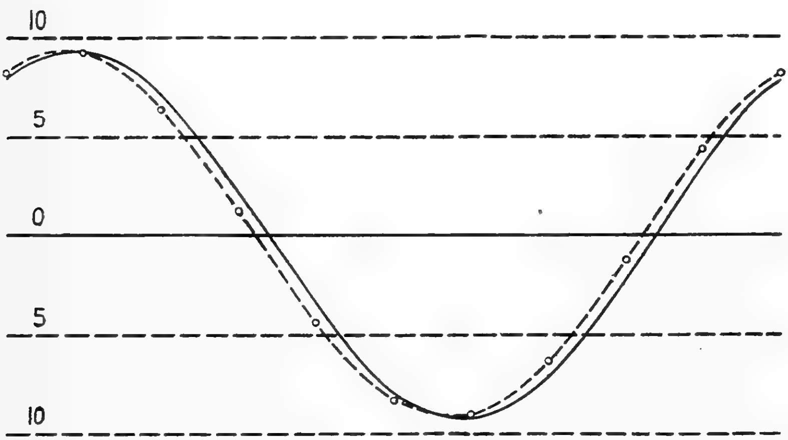


FIG. 5.—E–W semi-diurnal lunar tide for entire year. Dotted curve from observed values

$$y=9.380 \sin(\phi+63^\circ 56')$$

Full curve from 0.7 of calculated values

$$y=9.485 \sin(\theta+58^\circ 10')$$
$$R=0.7 \quad c/d=0.692. \quad \Delta\phi=5^\circ 46'$$

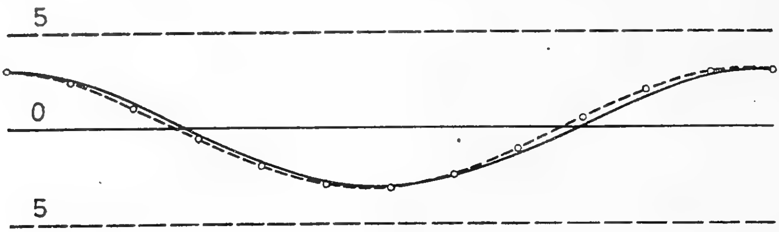


FIG. 6.—N–S solar tide for entire year. Dotted curve from observed values

$$y=3.140 \sin(\theta+99°25')$$

Full curve from 0.7 of calculated value

$$y=3.063 \sin(\theta+93°20')$$
$$R=0.7\ a/b=0.718. \quad \Delta\phi=6°5'$$

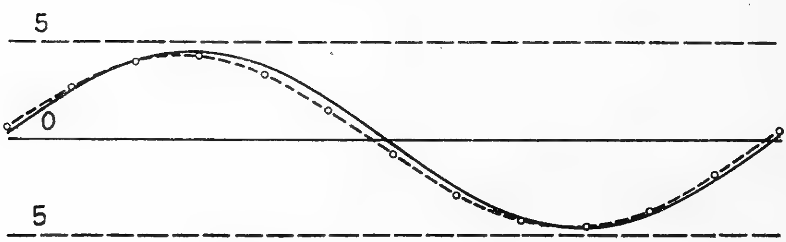


FIG. 7.—E–W solar tide for entire year. Dotted curve from observed values

$$y=4.399 \sin(\theta+8°6')$$

Full curve from 0.7 of calculated value

$$y=4.522 \sin(\theta+2°23')$$
$$R=0.7\ c/d=0.681. \quad \Delta\phi=5°43'$$

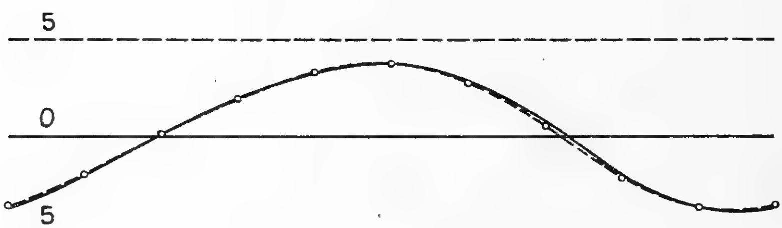


FIG. 8.—E–W diurnal lunar tide for entire year. Dotted curve from observed values

$$y=3.759 \sin(\theta+284°55')$$

Full curve from 0.7 of calculated values

$$y=3.799 \sin(\theta+282°53')$$
$$R=0.7\ c/d=0.693. \quad \Delta\phi=1°33'$$

well as for the thirteen months. A calculation for 306 periods was also made, omitting this month from both the observed and calculated data. This value is given opposite Y_{12}.

In the case of the N–S diurnal tide it will be noted that the amplitude is very small, about 0.5 fringe, as it should be since this tide has the coefficient cos $2l$, where l is the latitude. For Yerkes Observatory $\cos 2l = 0.0848$. This tide is too small to admit of much accuracy in the determination, but the results are included, as they are not without interest. Mean values are added for the whole year, and the means omitting the fourth month, and also omitting both the third and the fourth. The calculations are also added for the year as a whole, 326 periods; omitting the fourth month, 306 periods; and omitting both the third and fourth months, 282 periods. The omission of these months is perhaps justified, since both R and $\Delta\phi$ are decidedly abnormal. The mean of the six values gives $R = 0.584$ and $\Delta\phi = 7°46'$. Probably the only conclusion which is justified for the N–S diurnal tide is that R is about $0.6 \pm .2$ and that the difference of phase is small.

An effort was made to deduce the fortnightly lunar tide of period 13.66 days. Here the E–W tide should be zero, and the residual sine curves were less than 0.05 fringe from both the calculated and observed curves. The N–S tide, however, had an amplitude of about 1.8 fringes and gave $R = 0.628$ and $\Delta\phi = -8°24'$, quantities which agree as well as could be expected with the shorter periods. The negative sign of $\Delta\phi$ merely indicates that the uncertainty is considerable.

The results are collected in Table VII. The value given in each case is the average of the mean value for the thirteen lunar months and the value deduced by treating all the observations in a single set, except in the case of the N–S diurnal tide, where the values given are the mean of the six determinations mentioned above, and in the case of the E–W diurnal tide, which is the mean of four similar determinations.

The amplitudes are those for the observed curves averaged as indicated above. The errors indicated for the different tides are the average differences from the means of the thirteen months, except in the case of the N–S diurnal tide, where it is simply an

estimate. In combining the different tides to get a mean in each direction, the ratios and phase differences were weighted in proportion to the amplitudes of the tides except that the N–S diurnal tide was omitted. The final means of R and $\Delta\phi$ are the mean values obtained by weighting the five determinations in this way.

TABLE VII

	N–S			E–W		
	Amp.	R	$\Delta\phi$	Amp.	R	$\Delta\phi$
Lunar semi-diurnal...	6.188	0.6765±.019	1°15′± 1°2′	9.376	0.6915±.007	5°54′±56′
Solar..............	3.150	0.716 ±.041	5°53′± 3°12′	4.429	.681 ±.018	5°30′±1°28′
Lunar diurnal.......	.408	0.584 ±.200	(7°46′±15°)	3.799	.698 ±.023	38′±3°28′
Weighted means...	....	0.6895	2°41′	....	0.6903	4°34′
Final values		**R=0.690±.004**			**$\Delta\phi$=4°**	

This seems to be the most logical procedure and is perhaps justified by the fact that the average difference from the mean for the different tides in each direction is roughly inversely proportional to the amplitude. The probable error, computed in the usual way, is given with the final value of R.

The final result indicates that the rigidity of the earth in the N–S and E–W directions is the same[1] and the ratio R is 0.690 with a probable error of ±0.004. That the viscous yielding of the earth is small is indicated by the small difference in phase between the observed and computed tides. It will be noted that the two solar tides appear to agree excellently in phase displacement with the E–W semi-diurnal tide and that for the N–S semi-diurnal, and probably also the E–W diurnal lunar tides the phase displacement is definitely smaller.

However, for lack of a better method of finding the means of the N–S and E–W phase displacement, each was averaged as the ratios were, that is, simply by weighting them in proportion to the amplitudes of the tides. This gives a displacement in phase of

[1] The preliminary experiment, through an error in computation, indicated a difference in the rigidities in the two directions. The ratio should have been 0.710 for both the N–S and E–W. See *Science*, October 3, 1919, p. 327.

the water tides in the N–S direction of $+2^\circ 41'$ and in the E–W direction $+4^\circ 34'$. Although it seems certain that the difference in phase is slightly larger in the E–W than in the N–S direction, a mean displacement of $+4.^\circ 0$ is probably correct to within 1°. If we take $R=0.690$, the tides in the actual earth are 0.310 of what they would be if the earth were fluid, and the value of $\Delta\phi$ equal to $4.^\circ 0$, for the displacement of the water tides means that the earth tides lag behind the impressed forces by this same amount.

It is desired to express appreciation of the interest taken in this work by Professor T. C. Chamberlin, Professor E. B. Frost, and Professor F. R. Moulton.

RYERSON LABORATORY
November 1919

A PECULIAR BELT OF OBLIQUE FAULTING

ROLLIN T. CHAMBERLIN
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The Rocky Mountain system is a belt of varying structure. Northward from northern Montana it is a sharply delineated chain bordered on its eastern margin throughout many degrees of latitude by great overthrust faults. But in central Montana the regular, linear, faulted chain loses much of its distinctiveness and gives way to an irregular group of scattered mountain clusters.[1] Farther south in Wyoming and Colorado the Rockies reassemble in a more definite continuous chain, but in these latitudes folding has replaced faulting as the dominant structure.

For the present paper it is important to note that in central and southern Montana the Rocky Mountain chain, which elsewhere constitutes the definite backbone of the continent, spreads out into a plexus of short minor ranges and isolated mountain groups. These reach far out into the Great Plains province, where each of the individual groups becomes essentially a unit by itself. Some have resulted from igneous outbursts, and exhibit the results of vertically acting forces fully as much as horizontal thrusting; others have arisen largely from faulting or folding. In consequence of this diversity of origin of the major features, the general region has been subjected to stresses of quite variable sorts. It is to emphasize the peculiar manifestation of some of these that the present paper is ventured.

From the vicinity of Billings, in the midst of this region of scattered uplifts, E. T. Hancock has recently described a very remarkable belt of faulting, some 56 miles in length and comprising over 90 separate faults, relatively close together and more or less parallel one to another.[2] A striking feature of the belt is that

[1] Rollin T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, XXVII (1919), pp. 147–48.

[2] E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey*, Bull. 691-D (1918), pp. 101–47.

the fault lines, practically without exception, are inclined in the neighborhood of 45° to the long dimension of the faulted strip (Fig. 1). Many of these faults are over 5 miles in length, while one slightly curving fault plane has been traced for fully 10 miles. A few of the shorter faults, however, are less than a mile in length. As mapped by Hancock, these faults cut through a region surfaced by the Colorado and Montana groups of the Cretaceous, and by the Lance formation of the early Tertiary.

Hancock has clearly brought out the fact that the belt of faulting is located on the flanks of two conspicuous domes, which are the two dominating folds of the Lake Basin field. These are the Big Coulee–Hailstone dome in the northwest portion of the area studied, and the end of the Big Horn Mountain anticline, which extends into the southeastern corner of the Lake Basin field.[1] Southeast of the Big Coulee–Hailstone dome, in the direction of its principal axis, is a minor circular uplift which the author has called the Broadview dome. Hancock has pointed out the fact that the most intense faulting occurred along the steeply dipping south flank of the Big Coulee–Hailstone dome and around the southeast side of the Broadview dome.[2] From the Broadview dome to the northwest end of the Big Horn Mountain anticline very few faults were observed, but on the northwest slopes of the latter uplift they again become numerous. In short, the faulted strip follows the southern flank of the Big Coulee–Hailstone dome (including its satellite, the Broadview dome) and, after crossing an intermediate area where there are fewer faults, continues in nearly a straight line along the northern flank of the Big Horn uplift.

Both the doming and the faulting, which may perhaps be termed the local structural features of the Lake Basin field, are regarded by the author as in all probability related in origin to the major structures of the general region, and to have been determined more or less by the complex forces involved in the development of these major structures. "The mountain masses whose development has probably been the most active in determining the nature of the minor structural features in the vicinity of the Lake Basin field

[1] *Ibid.*, pp. 133–34. [2] *Ibid.*, p. 136.

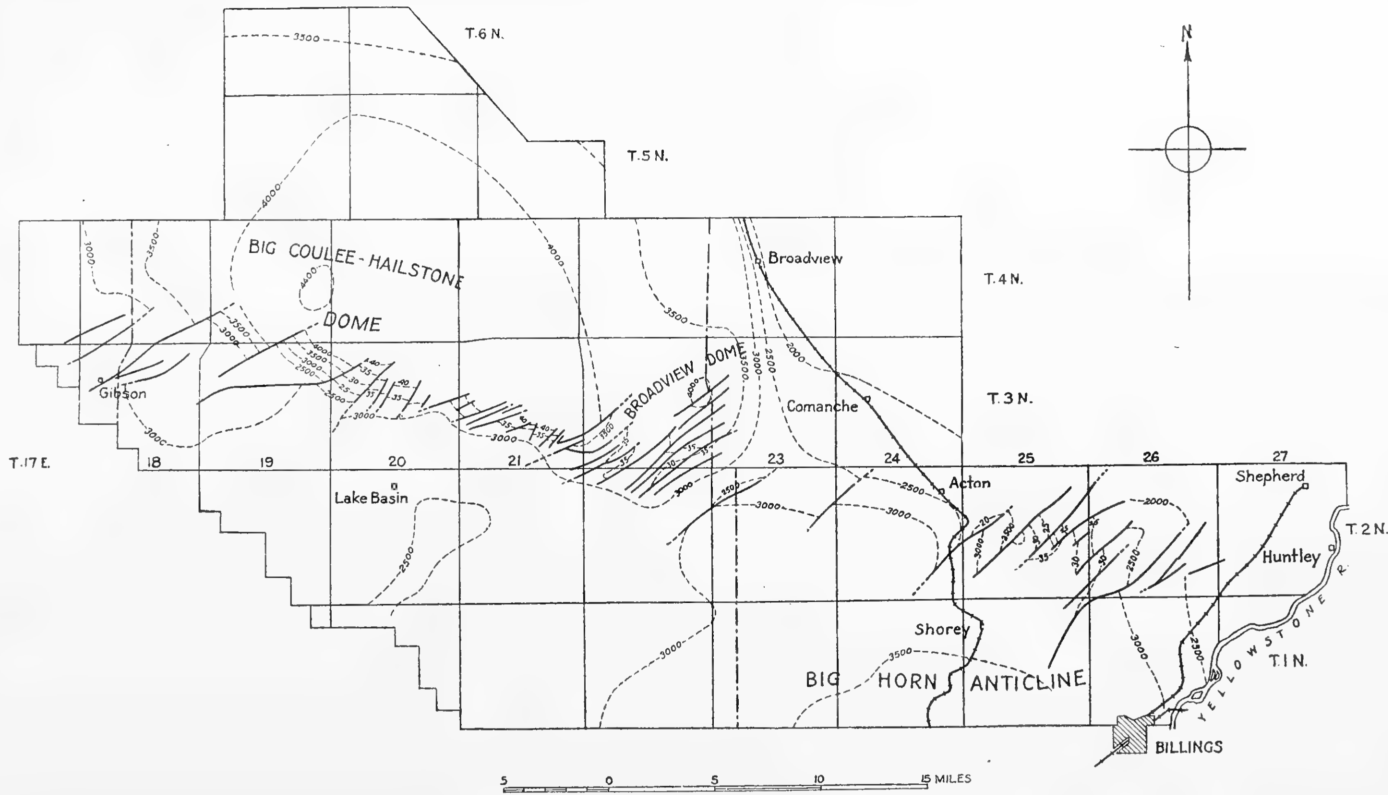


FIG. 1.—Map of the belt of faults in the Lake Basin field, Montana. The individual faults are inclined in the neighborhood of 45° to the long dimension of the belt. The dotted lines represent the structure contours on the base of the Eagle sandstone. Contour interval 500 feet. These contours depict the Big Coulee–Hailstone dome in the northwest portion of the area and the end of the Big Horn uplift in the southeast portion. (Redrawn from E. T. Hancock.)

are the Big Snowy Mountains on the north, the Little Belt Mountains on the northwest, the Snowy Range on the southwest, and the Big Horn Mountains on the southeast."[1] In three of these ranges the uplift has been so great that the pre-Cambrian complex is now exposed in the central core. Igneous outbursts have occurred in the general region, though not recognized within the Lake Basin field itself. The general setting of this remarkable faulting is admirably portrayed in this *Bulletin*, and many suggestive details are brought to the front, but as no definite explanation of the faulting is offered, I herewith venture to suggest some of the possible factors which may have given rise to the phenomenon.

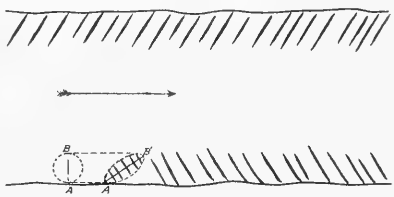


FIG. 2.—Diagram to illustrate the formation of oblique crevasses along the margins of a glacier moving in the direction indicated by the arrow. The crevasses point upstream as they extend toward the middle of the glacier where the motion is more rapid.

POSSIBLE EXPLANATIONS

There are two familiar processes which are known to produce parallel fracturing in a zone such as described. The first is illustrated by the development of oblique crevasses along the margins of valley glaciers. As the middle portion of a glacier moves more rapidly than the ice near the sides, a line on the glacier connecting points A and B (Fig. 2) will, after a time, become A′B′.[2] Since A′B′ is longer than AB, there has been stretching along that line. In fact, it can readily be shown that A′B′ represents the direction of elongation, or major axis of the strain ellipsoid, as developed by Leith.[3] Tension therefore develops along this line, and is relieved by fractures at right angles to it. Hence it is that the lateral margins of valley glaciers are commonly riven by a great

[1] E. T. Hancock, *op. cit.*, p. 132.

[2] John Tyndall, *Glaciers of the Alps* (1860), pp. 318–19.

[3] C. K. Leith, *Structural Geology* (1913), pp. 16–21.

It is of course to be recognized that, since the rate of motion changes more rapidly near the margin of the glacier than toward the middle, the line A′B′ will be curved instead of straight, and ideally the relation should be represented by many small strain ellipsoids instead of one large one.

succession of parallel crevasses which point obliquely upstream as they extend in toward the middle of the glacier. Such a belt of crevasses bears some resemblance to the belt of faults in the Lake Basin field.

The other process which is known to produce results of this kind is torsion. Its behavior has been strikingly illustrated by the familiar experiment of Daubrée, who subjected a long plate of glass to torsional stress.[1] The result was to produce numerous fractures in two distinct sets which crossed each other approximately at right angles (Fig. 3). The fractures of each set were nearly parallel to one another, and were inclined approximately at 45° to the axis of torsion. Either set of parallel fractures would look much like the strip of faults in the Lake Basin field, provided the other intersecting set did not form.

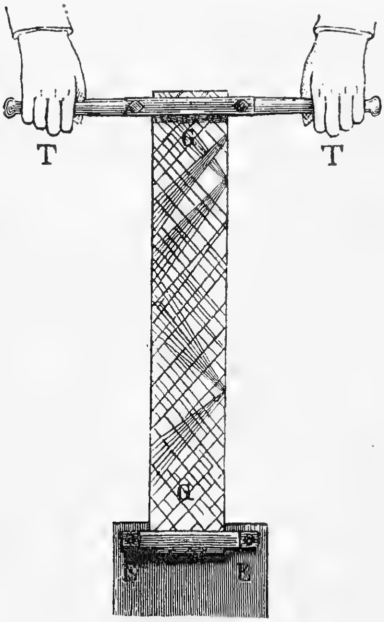


FIG. 3.—Fractures developed in a glass plate by torsion. The two sets of fractures are nearly at right angles to each other and inclined 45° to the axis of torsion. (From Daubrée.)

APPLICATION TO THE LAKE BASIN FAULTING

The most striking characteristic of this belt of faulting in Montana is the grouping of the faults in a long, narrow strip trending W.N.W. and E.S.E. Scarcely less conspicuous is the fact that, almost without exception, the individual fault traces are inclined to the axis of the belt at angles in the general vicinity of 45°. The third fact of prime significance appears to be that toward the west end of the belt the fracturing took place on the south flank of an uplifted tract, while toward the east end of

[1] G. A. Daubrée, *Études synthétiques de géologie expérimentale* (1879), Tome 1, pp. 307–15.

the belt the fracturing has occurred on the north flank of another distinct uplift. In the area between the two uplifts there has been some but noticeably very much less faulting than on the immediate flanks of the two uplifts. In the process of doming, the strata near the west end of the faulted strip were uplifted on the north and given a southerly tilt, while near the east end of the zone of faulting the strata were uplifted on the south and thus given a northerly tilt. Thus the two ends of the faulted area were tilted in opposite directions. Such an opposite movement involves a certain amount of twisting, or torsion. The axis of the twist would coincide with the long axis of the present fault belt. If the strains developed in this adjustment between the oppositely tilted areas were sufficiently great, they would produce fracturing along planes inclined approximately 45° to the axis of torsion, or long dimension of the present faulted belt. Daubrée's experiment would suggest that these fractures should occur in two sets crossing each other at right angles. One such set, to the number of more than 90 faults, is in just the position to meet the requirements, but the complementary set, with the exception of two very short faults northeast of the Broadview dome, is lacking.

The explanation of the failure of the cross-fractures to open is sought in the trend of the axis of torsion, whose general direction hovers around N.80°W. The fractures of the set which actually did form have a N.E.-S.W. trend. If the complementary set of fractures had developed, they also should have opened in planes inclined 45° to the axis of torsion and at right angles to the first set, which would place them in the neighborhood of N.35°W. It will be observed that this last figure is not far from the general trend of the adjacent portion of the Rocky Mountains. The Rocky Mountains owe their formation, for the most part, to compressive stress. While the exact stress-strain relations involved in the development of this portion of the Rocky Mountains are not known with certainty, it is, however, certain that an effective component of compressive stress (whether the strain were rotational or non-rotational) has operated at right angles to their long dimension, and so also in a direction at right angles to the postulated possible cross-fractures. Hence any such N.W.-S.E. fractures,

which might otherwise have developed in response to the local tension developed by the torsion, might be prevented from forming by the Rocky Mountain compressive stresses, provided the torsion came at a time when the Cordilleran compressive stresses were still operative. This would not seem an unreasonable assumption since the Rocky Mountain province has been subjected to such stresses during much of Cenozoic time.

But, according to Becker, if faulting takes place because of torsion, the faults should be inclined in the same sense as the thread of a right-handed screw, when the twisting has been clockwise, as it seems to have been in the Lake Basin field case.[1] This would be in consequence of the nature of the strain at or near the surface of the earth. There the direction of elongation should be N.E.-S.W. and fracturing on this principle should occur along lines trending N.W.-S.E. On the other hand, an analysis by the strain-ellipsoid method shows that if a body having two parallel sides, like Daubrée's glass plate, be twisted, the axes of strain on the opposite sides are exactly reversed. In Daubrée's experiment both sets of torsion fractures were about equally developed. This was because the strains developed on the two faces of the glass plate were about equally effective in causing the fracturing of the plate.

For confirmation of these principles, paraffine was molded into strips having the dimensions $12 \times 2 \times \frac{1}{2}$ inches. The ends of these strips were then twisted clockwise as in the Lake Basin case. Each strip snapped apart along a single fracture surface. The fracture in 10 different tests was in accordance with the orientation observed in Montana. In 11 tests it was contrary, the fracturing belonging to the cross set. In every test, without exception, the fracture occurred not far from 45° to the axis of torsion. These tests would seem to indicate that in strips, or plates, of the sort used, neither set of fractures takes real precedence over the other in forming. But in the earth the underside of the paraffine block finds no exact counterpart, and the strain conditions on the upper surface should dominate. Hence, other things being equal, there is greater likelihood that the right-hand-screw fractures

[1] G. F. Becker, "The Torsional Theory of Joints," *Trans. Amer. Inst. Min. Eng.*, XXIV (1894), pp. 130–38.

will be produced. This would be the set at right angles to those actually occurring in the Lake Basin field.

Becker has also stated that, if due to torsion, each master fault will be a reverse fault, and the fissures will gape from the start.[1] Examination of the fracture planes in the paraffine tests revealed the fact that many of them were straight across or, expressed in terms of structural geology, were vertical faults. In others the fault surface was somewhat inclined from the vertical, or was vertical for a portion of the distance and then curved. Where the fault plane was inclined from the vertical the relations were, as Becker has stated, those of a reverse fault. The hanging wall was elevated with respect to the foot wall. The paraffine tests also confirmed Becker's statement that the fissures will gape. This does very well in an experiment where the weight of materials plays no important part. But reverse faults which gape would be a curiosity in the earth. While in the earth, just as in the experiment, the twisting would tend to cause this relation, on the other hand the gravity of the earth, in co-operation with the tension developed by the torsion, should offset this tendency. If the twist developing such a series of parallel faults were accompanied by much tension, downsliding of the blocks should be expected. As there seem to be special grounds for expecting tension, independently of the torsion, in the case under consideration, reverse faulting as the dominant type in this particular strip in Montana would seem unlikely.

Furthermore the strains developed by the doming process above outlined would, in all probability, not be of a very intense sort unless there were also counterpart downwarping north of the Big Horn uplift and a depression of the basin south of the Big Coulee–Hailstone dome to complete the twist. Some depression of the basins seems likely, but the twisting was probably not violent. Hence the fracturing, so far as due to torsion alone, should be not far from vertical, and the tendency toward reverse faulting would be slight. Nevertheless in this connection it is interesting to note that reverse faults actually do occur in one section of the fault belt under consideration.[2] Normal faulting, however, dominates.

[1] G. F. Becker, *op. cit.*, p. 137.

[2] E. T. Hancock, *op. cit.*, p. 140.

From the foregoing inspection of the problem, it would seem clear that this remarkable strip of oblique faults has not been produced by simple torsion alone. The observed facts are at variance in several essential particulars with what the theory of pure torsion should require. The genesis of the faults must have involved in addition other important factors. These are to be sought in an analysis of the larger structural features of the general region, and a consideration of the strains involved in their genesis.

A study of the map of Montana shows that, while the Rocky Mountain chain loses much of its regularity and individual linear character amidst the scattered mountain groups of west central Montana, there is nevertheless a prominent Rocky Mountain trend line which swings sharply eastward in southern Montana, and thence turns south again in the Big Horn range. This particular line of the Rockies thus follows a sigmoidal curve which is perhaps more conspicuous on a small-scale map than a map of a larger scale, for the reason that the details of the minor ranges, if they are too prominent, tend to obscure the larger relations. It was suggested by T. C. Chamberlin that this pronounced bend in the range may have been an important factor in the present problem. The great Lewis overthrust of northern Montana shows that the Glacier National Park region has been transported bodily eastward for at least 15 miles, and possibly much farther.[1] Southward from Glacier National Park the easterly overriding upon the thrust plane gradually diminished, but in any case, even where the faulting has given way to folding as the dominant process, the formation of the Rocky Mountain structure involved an eastward movement of the crumpled and faulted materials. To accomplish the crustal shortening involved in the folding, the main mass of the Big Horn Mountains should have moved eastward to some extent, on the assumption that the deformation was due to thrusting from the Pacific.

The northwestern extremity of the Big Horn anticline, as already stated, extends into the southeastern corner of the area under consideration. Thence westward to the Crazy Mountains

[1] M. R. Campbell, "The Glacier National Park," *U.S. Geol. Survey*, Bull. 600 (1914), p. 12.

the system is poorly developed. This poorly developed tract lies on the border of the eastward-trending portion of the Rocky Mountain belt, which connects its overthrust tract in northern Montana with its south-trending tract in Wyoming and Colorado. Because of its general east-west trend, it was not in a position to be much folded by a thrust from the Pacific, but on the contrary was well placed to receive elongation from the greater eastward thrust of the Rocky Mountains farther to the south. The Big Horn Mountains seem to partake in some measure of both these attitudes, for the southern portion trends with the Rockies in Wyoming and Colorado, while the northern portion veers round to a more westerly trend, and dies down in the Lake Basin district on the very border of the fault belt which, in striking eastward from the Big Coulee–Hailstone dome, is almost tangent to the northern flank of the range.

From these relations it will be seen that, though the deformation on the border of the Lake Basin was limited and gentle, there would naturally have been some eastward movement at the Big Horn end. On the other hand, the Big Coulee–Hailstone dome at the northwesterly end lay on the Great Plains side of the fault belt, in the lee of the less-moved portion of the Rocky Mountain belt, and appears also to be more nearly related to the group of igneous intrusions than to the folded belts, and so should have been less affected than the Big Horn end by the eastward movement. Hence it is inferred that the southern portion of the Lake Basin field, which was most influenced by the Big Horn deformation, was shifted eastward, while the northern portion partook rather more of the relative fixity of the Great Plains province and the area of igneous intrusions. The differential motion involved in this adjustment is not unlike that which produces the oblique crevasses along the margins of glaciers, except that the differential movement was distributed, instead of having a limit at a sharp borderline of slippage such as lies at the junction of the moving glacier with the wall of the valley. No such line of sharp differentiation is of course assignable to the rather broad and gentle movements in the Lake Basin. There may of course have been a concealed longitudinal shear plane deep below the fault

belt, but as the map shows only small oblique faults, this supposition has little or no tangible support and need not be seriously considered here, as the movements already discussed would still be needed to explain the oblique faults. If any underlying longitudinal fault is to be postulated, a group of such faults with distributive action would best fit the case.

On the glacier principle, the southern portion of the district, moving eastward relative to the northern portion, should cause repeated crevasse-like fractures to open along a belt where the strain from the differential motion was greatest. As the south side of the belt moved eastward with respect to the northern side, tension would be developed along N.W.-S.E. lines obliquely across the disturbed zone. The result would be a large number of fracture lines at right angles to the direction of tension, or running N.E. and S.W., as in the upper part of Figure 2. The oblique crevasses in a glacier point upstream as they extend toward the middle of the glacier, or toward the more rapidly moving portion. Hence in this fault problem the fractures should be inclined toward the direction from which the relative motion came. This is just what was observed in the faulted zone of the Lake Basin field. It is then only necessary to suppose that the zone of yielding between the differently moving areas was located where the faults have developed.

Near the eastern end of the fracture belt the downthrow side of nearly all of the faults is toward the northwest. As these are normal faults, most of the fault planes dip to the northwest. On the other hand, near the western end of the belt the downthrow side, and hence also the dip, of the majority of the fault planes is toward the southeast, though the faulting is less regular at this end than at the other. The downslipping in general has thus been from the ends toward the middle of the belt, though the generalization is not so well substantiated in the western half flanking the Big Coulee–Hailstone dome as it is in the more regular eastern half bordering the Big Horn uplift. The dome at either extremity represents a relative upthrust which, if the result of igneous activity beneath, necessarily adds a further element of tension, thus favoring an increase in the number of fractures upon

the flanks of the domes, while at the same time it tends to give the observed slopes to the fault planes.

This peculiar belt of oblique faulting is therefore attributed to the eastward movement of the southern portion of the region relative to the northern, together with the local torsion and incidental tension developed by the doming process.

THE PALEOZOIC SECTION OF THE TOMAH AND SPARTA QUADRANGLES, WISCONSIN[1]

W. H. TWENHOFEL AND F. T. THWAITES
University of Wisconsin

INTRODUCTION

The Tomah and Sparta quadrangles lie wholly within and on the northeastern edge of the Driftless Area of western Wisconsin. The first-named quadrangle is directly east of the latter. There are 431 square miles in the two areas.

Little geologic work directly relating to the two quadrangles has been published. As parts of the Driftless Area they have received the attention of many of the students who have been concerned with its peculiar problems. Three university theses which directly relate to the whole or parts of the two quadrangles have been written, but none of these has been published.[2] A short paper by W. D. Shipton gives a description of fulgurites[3] found by him near Sparta, and the same author in a second short paper proposed a new formational term for the fine-grained and shaley sandstones which constitute the middle portion of the exposed Cambrian.[4] Other papers which in some degree bear on the geology of the two quadrangles are Ulrich's "Revision of the Paleozoic Systems,"[5] Bassler's "Bibliographic Index of American Ordovician and Silurian Fossils,"[6] in which is given a geologic section

[1] Published by permission of the state geologist of Wisconsin.

[2] R. B. Johns, "The Physiography and Geology of the La Crosse River Valley." Unpublished thesis, University of Wisconsin, 1900. W. D. Shipton, "The Geology of the Sparta Quadrangle." Unpublished thesis, University of Iowa, 1916. W. O. Blanchard, "The Geography of the Tomah-Sparta Quadrangles." Unpublished thesis, University of Wisconsin, 1917.

[3] W. D. Shipton, "A Note on Fulgurites from Sparta," *Proc. Iowa Acad. Sci.*, XXIII (1916), 141.

[4] W. D. Shipton, "A New Stratigraphic Horizon in the Cambrian System of Wisconsin," *ibid.*, pp. 142–45.

[5] E. O. Ulrich, *Bull. Geol. Soc. Amer.*, XXII (1911), Pl. XXVII.

[6] R. S. Bassler, *Bull. 92, United States National Museum*, II (1915), Pl. II.

for Wisconsin, and one of Walcott's papers, in which is defined the geologic section for western Wisconsin as worked out by Ulrich.[1] The latest published work relating to the areas is an abstract of a paper read before the Geological Society of America at the Albany meeting. This paper describes the rock terraces which are such conspicuous features of the surface.[2]

DESCRIPTION OF THE GEOLOGIC SECTION

Only rocks of sedimentary origin are exposed in the Tomah and Sparta quadrangles (Fig. 1). Of these there are two groups: an older, consisting of poorly cemented sandstones and compact, firm dolomites, both of Paleozoic age; and a younger, made up of unconsolidated materials of very late geologic time. With the latter this article is not concerned. The strata of both groups are in essentially undisturbed position.

The Paleozoic strata belong to the Cambrian and Ordovician systems.[3] The exposed thickness aggregates between 700 and 800 feet, while wells which have been drilled to the base of the sedimentary sequence show the presence of an additional thickness of about 350 feet. These unexposed strata are of Cambrian age.

CHARACTER AND ROCKS OF THE PRE-CAMBRIAN FLOOR

The rocks composing the pre-Cambrian floor beneath the Paleozoic sediments are known from deep wells and from exposures some miles to the north. Drillings from a well in Tomah indicate a gneiss of medium texture, composed of clear and milky quartz, pink feldspar, and white mica. The nearest exposures to the north are at Black River Falls, where the pre-Cambrian rocks consist of granites, gneisses, diorites, schists, and iron formation.

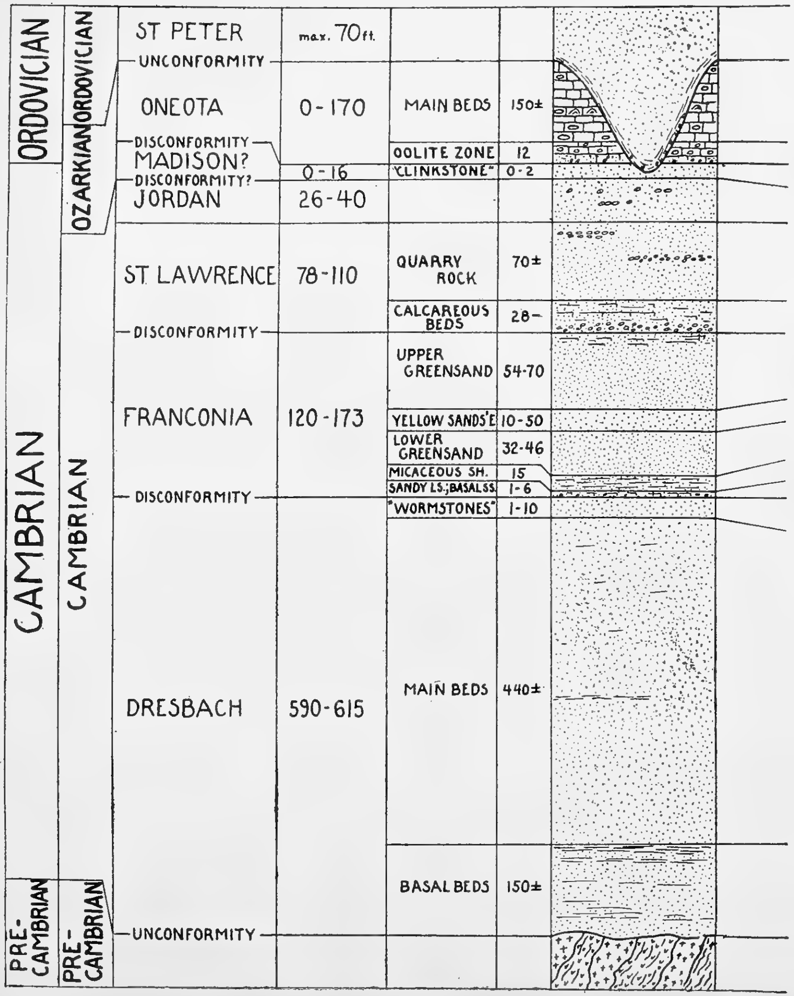
The exposures of the contact between the Paleozoic and pre-Cambrian rocks and the wells in this and adjacent districts which

[1] C. D. Walcott, "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, LVII, No. 13 (1914), 354.

[2] Lawrence Martin, "Rock Terraces of the Driftless Area of Wisconsin," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 148–49.

[3] If the classification of Dr. E. O. Ulrich be followed, there would be three systems represented: Cambrian, Ozarkian, and Ordovician. Fig. 1 shows the groupings of the systems according to the general usage and also according to the proposals of Dr. Ulrich.

GENERALIZED PALEOZOIC SECTION OF THE TOMAH-SPARTA QUADRANGLES, WISCONSIN



St. Peter. Sandstone, fine- to medium-grained, yellow to brown, locally casehardened, bedding heavy to thin, cross-laminated; at base beds of red and green shale resting on residual clay and chert of Oneota.

Oneota (main). Dolomite, medium-grained, gray to drab, bedding medium to thick, many *Cryptozoa*, rare silicified shells, gray, yellow, and red chert nodules.

Oneota (basal). Dolomite and chert as above, both in part oölitic, beds of sandy dolomite and white and yellow medium- and fine-grained dolomitic sandstone with sandstone and dolomitic pebbles and fragments of green shale.

Madison (?). Sandstone, medium- to coarse-grained, yellow to white, heavy-bedded, quartzite at top (the "clinkstone").

Jordan. Sandstone, coarse- to medium-grained, yellow to gray, heavy-bedded, cross-laminated and cross-bedded, scattered sandstone pebbles; not clearly separated from underlying formation.

St. Lawrence (quarry rock). Sandstone, fine-grained, yellow to white, thin-laminated to heavy-bedded, cross-laminated, mud cracks near base and middle, several conglomerate beds with sandstone pebbles, in part edgewise conglomerate, worm holes and fossil impressions abundant in some layers.

St. Lawrence (calc. beds). Sandstone, very fine-grained to shaley, yellow to light brown, very dolomitic in some beds, local thin beds of gray and purple mottled dolomite, fossiliferous; greensand conglomerate at base.

Upper greensand. Sandstone, fine-grained, light yellow to green, thin to medium bedding, cross-laminated; yellow layers very calcareous, some layers very glauconitic, sparingly fossiliferous.

Yellow sandstone. Sandstone, fine-grained, yellow to gray, heavy-bedded.

Lower greensand. Sandstone, fine-grained, gray to green, thin- to thick-bedded, mud-cracked, highly cross-laminated, with short fore-sets, current and wave ripple-marked, glauconitic, fossiliferous.

Micaceous shale. Fine-grained shaley sandstone, micaceous, thin-bedded, light yellow.

Basal beds. Sandy limestone, pink to brown, glauconitic, fossiliferous; sandstone, coarse- to medium-grained, rough-bedded, conglomeratic with sandstone pebbles, cross-laminated.

"Wormstones." Sandstone, coarse- to medium-grained, gray to brown, beds about 1 foot thick composed of firm sandstone, in which are large vertical worm holes ("wormstones") alternating with thinner beds of soft white sandstone with limonite and siliceous concretions (nodular layers).

Main beds. Sandstone, medium- to coarse-grained, light yellow to gray, bedding medium to heavy, wave and current ripple marks, rare mud cracks, cross-laminated, thin laminae of green shale, possibly a local shale bed a few feet thick about 250 feet below top, local limonite cemented beds. Lower 150 feet known only in wells.

Basal beds. Sandstone as above with beds of red, green, and black sandy shale, shale beds of variable thickness up to perhaps half a dozen feet. Known only in wells.

Pre-C. Granite, gneiss, etc. Known only in wells.

FIG. 1

have been drilled to this contact suggest that the pre-Cambrian lands had been reduced to slight relief before the deposition of the Cambrian sands.

THE CAMBRIAN SYSTEM

Sandstones compose nearly the whole of the Cambrian rocks of the two quadrangles. Some of the finer-grained sandstones have been called shales, but were most of such in association with true shales they quite certainly would be called sandstones. True clay shales are present only as thin laminae and lenses. Dolomite and dolomitic sandstones of local and horizontal distribution also occur. The basal strata of those exposed consist almost wholly of quartz sandstones. The sands are commonly clean and well sorted. The higher Cambrian strata are also largely composed of quartz sands, but some portions contain an abundance of greensand. The top of the Cambrian is quite sharply defined from the base of the Ordovician by the rather general occurrence near the contact of quartzite-like gray sandstones and by the great differences between the dolomite of the basal Ordovician and the sandstone of the highest member of the Cambrian.

Four Cambrian formations are exposed. These, in ascending order, are (1) the Dresbach sandstones, (2) the Franconia glauconitic and shaley sandstones, (3) the St. Lawrence sandstones and dolomitic shales with occasional dolomite layers, and (4) the Jordan sandstones. There is a possibility that a fifth Cambrian formation is present, since at the top of the Cambrian sequence there are a few feet of strata which somewhat resemble the Madison sandstone. The 350 feet of unexposed strata may contain the Eau Claire and Mount Simon formations of Dr. Ulrich's section. The total thickness of the Cambrian is about 900 feet (Fig. 2).

The Cambrian sediments were deposited in shallow water above wave-base. This is proved by the abundant occurrence of both wave and current ripple mark and the wonderful development of cross-lamination in which there are steep fore-sets up to 50 feet in length. Mud cracks, which are present in at least three horizons, prove that at times the sediments were exposed to the drying effects of the sun. The rounding, sorting, and cross-lamination of some of the sands suggest local eolian deposition.

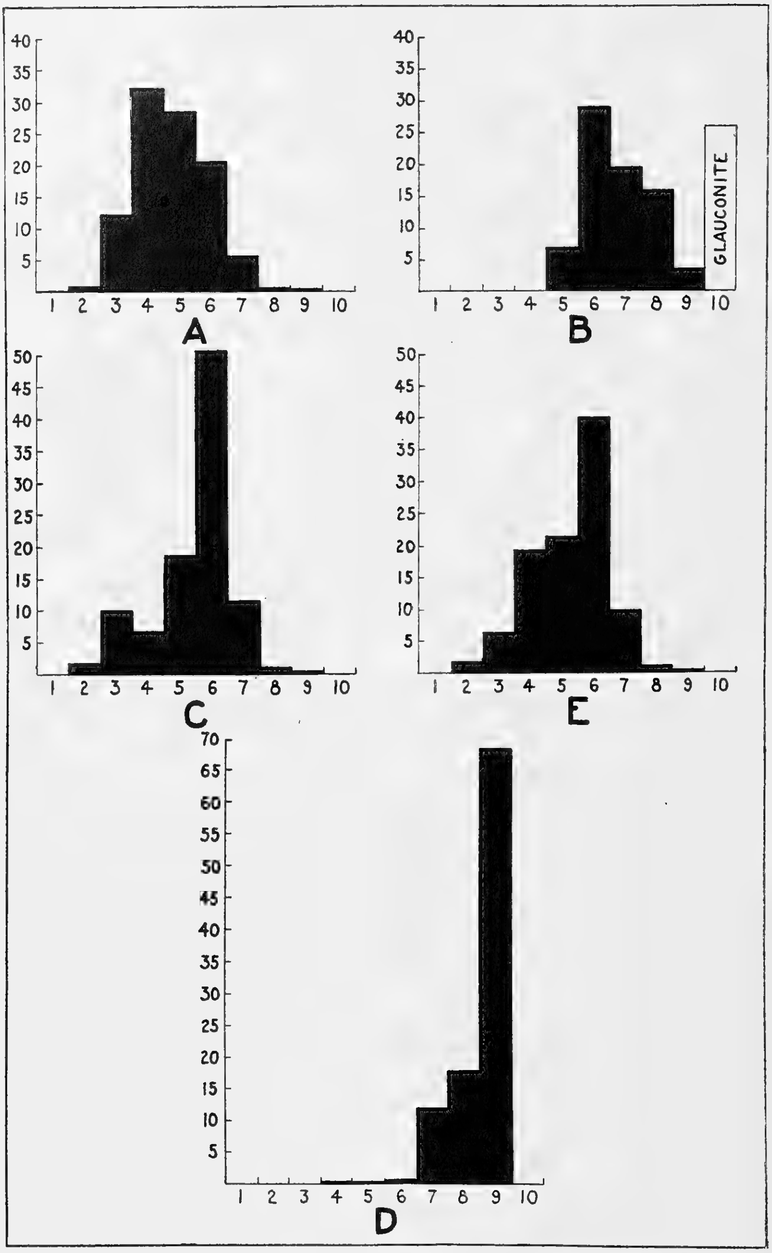


FIG. 2.—Mechanical analyses of characteristic sands (for description see opposite page).

EXPLANATION OF THE DIAGRAMS OF FIG. 2

The ordinates represent percentages by weight, the sum of all the rectangles in each diagram totaling 100 per cent. Abscissae represent the dimensions of the quantity indicated by the rectangle immediately above it. These for convenience are numbered 1 to 10, the dimensions corresponding to the numbers being as given below. The analyses were made with Tyler Standard Screen Scale Testing sieves:

1. Between 1.168 and .833 mm.
2. Between .833 and .589 mm.
3. Between .589 and .417 mm.
4. Between .417 and .295 mm.
5. Between .295 and .208 mm.
6. Between .208 and .147 mm.
7. Between .147 and .104 mm.
8. Between .104 and .074 mm.
9. Smaller than .074 mm.
10. This does not represent dimensions, but material which is different from the main body of the sand. The loss in sifting (generally less than 1 per cent) has been added to No. 9, as the finest grades suffer the greatest loss.

A. Dresbach sandstone, Tunnel City, 65 feet from the top of formation.

	Percentage	
1.	0.036,	spherical grains of transparent quartz.
2.	0.755,	well-rounded grains of transparent quartz.
3.	12.080,	transparent quartz, most grains well rounded, a few subangular.
4.	32.120,	transparent quartz, grains well rounded to subangular.
5.	28.270,	transparent quartz, grains well rounded to subangular, a few grains angular.
6.	20.460,	transparent quartz, estimated 10 per cent angular, 25 per cent well rounded.
7.	5.600,	transparent quartz, a few grains well rounded, most subangular to angular.
8.	0.312,	transparent quartz, nearly all grains sharply angular.
9.	0.367,	transparent quartz, grains angular.

This sand is of beach origin.

B. Lower greensand of the Franconia formation, collected at Boscobel on the Wisconsin River, south of the quadrangles.

	Percentage
1.	0.00.
2.	0.00.
3.	0.00.
4.	0.00.

Percentage

5. 6.83, transparent quartz, grains subangular to angular.
6. 28.80, essentially no rounding.
7. 19.27, no rounding, a little dolomite.
8. 15.71, as No. 7.
9. 3.47, as No. 7, with about 10 per cent dolomite.
10. 25.84, this rectangle represents the glauconite present in the sample.

This sand was deposited some distance from the belt of constant wave-wash as shown by its fineness and little rounding.

C. Fine-grained sandstone from near base of the Jordan, Jeff Davis Rock, Tomah quadrangle.

Percentage

1. 0.00.
2. 1.78, transparent quartz, grains highly spherical and pitted.
3. 10.00, transparent quartz, high sphericity, grains pitted.
4. 6.45, transparent quartz, high sphericity, grains pitted, estimated 5 per cent subangular.
5. 18.52, transparent quartz, with a few grains of limonite, grains well rounded and pitted, 5 per cent subangular.
6. 50.50, as No. 5.
7. 11.29, transparent quartz, well rounded with a few angular grains.
8. 1.06, transparent quartz, 60 per cent subangular to angular.
9. 0.40, transparent quartz, with a little clay, and dolomite, about 5 per cent rounded, about 10 per cent aggregates of finely divided quartz.

The assortment, rounding, and cross-lamination of this sand suggest wind deposition.

D. St. Lawrence sandstone, 2 miles southeast of Norwalk, Wis., 50 feet below base of Oneota. Contains marine fossils.

Percentage

1. 0.00.
2. 0.00.
3. 0.00.
4. 0.40, transparent quartz, grains rounded.
5. 0.36, transparent quartz, rounded and subangular grains, estimated 10 per cent muscovite flakes.
6. 0.60, as No. 5.
7. 12.00, transparent quartz, angular grains, occasional muscovite flakes and limonite grains, a little dolomite.
8. 17.92, transparent quartz, nearly all grains angular.
9. 68.72, transparent quartz, 75 per cent aggregates, no rounding whatever.

The last rectangle does not express the actual facts as it is composed of grains varying from .074 mm. in diameter to dimensions fully one one-hundredth of that dimension. This sand was deposited beyond the zone of constant wave-wash.

E. St. Peter sandstone, Cashton, on the southwestern edge of the Sparta quadrangle, estimated 30 feet above the base.

	Percentage
1.	0.00.
2.	1.80, transparent quartz, high sphericity.
3.	6.28, as No. 2.
4.	19.21, as No. 3.
5.	21.42, transparent quartz with a few limonite grains and fragments of calcite, most well rounded, but numerous subangular grains.
6.	40.00, transparent quartz with a few grains of limonite, well rounded, estimated 25 per cent subangular.
7.	9.81, as No. 6, 50–60 per cent subangular, 10 per cent angular with no rounding.
8.	1.13, transparent quartz, 75 per cent sharply angular, rest subangular.
9.	0.352, transparent quartz, with rare garnet grains, essentially all angular.

The assortment, rounding, and cross-lamination of this sand suggest wind deposition.

Save for local and horizonal exceptions, the Cambrian sandstones are poorly cemented. Most of the beds crumble on slight exposure and in numerous places fresh rock may be crushed to sand with the hands.

THE DRESBACH FORMATION

The type locality for the Dresbach formation, first called the "Dresbach sand rock," is at Dresbach, Winona County, Minnesota, 18 miles west of this area. At Dresbach the character and sequence of the strata appear to be quite similar to what they are in these quadrangles, although lower shaley strata are present there which have not been differentiated in this area.[1] What is known of the unexposed Cambrian strata of these two quadrangles is included in the description of the Dresbach formation, although it is quite possible that these strata contain the Eau Claire and Mount Simon formations.

The Dresbach strata immediately underlie the lower lands of the two quadrangles. Where the formation has been completely uncovered through the removal of the higher formations, there has

[1] N. H. Winchell, *Minn. Geol. and Nat. Hist. Surv., Final Rept.*, II (1888), xxi.

developed a gently rounded, discontinuously terraced topography. Along the deeper valleys, in such places where the overlying formation has not been completely removed, the upper strata of the Dresbach rise from steep slopes to form coalescing tower-like cliffs or conical buttes.

Characteristics.—The exposed strata of the Dresbach consist of poorly cemented quartz sandstones of which the grains are clean and well rounded. In most of the beds the assortment is extremely good. Interlaminated with the exposed sandstones are thin lenses (up to about a centimeter in thickness) of green sandy shale. Well records show the presence in the unexposed strata of greenish, bluish, and reddish shale. Most of these occur about 450 feet below the top of the Dresbach and may represent a part of the Eau Claire formation. The sands are generally poorly cemented, and very few layers are sufficiently firm for use in construction. The colors vary from gray to yellow. "Iron rocks"—sands cemented by hydrous iron oxide—are locally present in considerable abundance, but are not characteristic of any horizon.

The strata are not continuous for long distances, and with the exception of worm-perforated beds, which are prominent in the upper horizons, it has not been found possible to identify any portion beyond the limits of a single exposure. In the field these upper strata were known as the "wormstones." Cross-lamination at variable inclinations with variable directions is present in nearly every outcrop. The fore-sets are generally short, 5 to 6 feet being the average maximum, but in an outlier near the village of Rockland there are fore-sets at angles of 15° to 20° which exceed 50 feet in length. The inclination of the long fore-set cross-lamination at Rockland is nearly due east. In a number of cases the cross-lamination has the appearance of having been produced by wind deposition. The nature of the Dresbach sediments was not favorable for the development of mud cracks, but such are present just east of Rockland in a horizon about 100 feet below the top of the formation.

The thickness of the exposed Dresbach is about 300 feet. Well records show that from 590 to 615 feet are present from the base of the Franconia formation to the pre-Cambrian floor.

Except for worm tubes, of which there appear to be at least two varieties, fossils have not been observed in the Dresbach sandstones of the two quadrangles. The most common worm tubes are of the Scolithus type. They are extremely abundant in the upper beds.

Conditions of origin.—The sediments of the Dresbach formation were accumulated in shallow water above wave-base or above water-level. It does not seem probable that at any time the waters attained sufficient depth to remove the sands from the wash of the waves. The possible eolian cross-lamination and certainly the mud cracks prove that at times the sites of deposition were above water-level. The writers' conception of the conditions of deposition is that of an extensive sand flat, of which parts may have been continuously underneath the water, other parts were exposed at low tide, while other areas—sand islands, bars, etc., thrown up by the waves and piled higher by the winds, the different environments shifting more or less from time to time—were above water-level. These conditions granted, the clean washing of the sands, the local thin laminae of shale, the presence of mud cracking, the abundance of both wave and current ripple mark, the excellent sorting of the sands in most of the beds and their quite perfect rounding in some beds, the great development of cross-lamination of which some appears to be eolian, the variable and lenticular character of Dresbach bedding, and the general absence of fossils follow as natural consequences, and it is difficult to conceive how all these characters could have developed on an extensive scale under any other conditions.

THE FRANCONIA FORMATION

The Franconia formation was defined by Berkey[1] without its upper and lower limits being stated. In some of the publications of the United States Geological Survey the strata which constitute the Franconia formation appear to have been included in the St. Lawrence,[2] which as thus defined includes two stratigraphic

[1] C. P. Berkey, "Geology of the St. Croix Dalles," *Amer. Geol.*, XX (1897), 373, 377.

[2] G. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southern Minnesota," *Water Supply Paper No. 256, U.S. Geol. Surv.* (1911), pp. 63–68; W. H. Morton and others, "Underground Water Resources of Iowa," *Water Supply Paper No. 293* (1912), Pl. II, p. 65.

units of decidedly different lithology which are separated by a quite generally well-exposed greensand conglomerate. The strata, which in this article are referred to the Franconia formation, are included between the top of the Dresbach and the base of this greensand conglomerate.

The Franconia strata cap divides over considerable portions of the northern halves of the two quadrangles. These have a rolling, more or less terraced, topography with mammillary knolls. Where overlain by higher strata the Franconia makes a terraced slope on which at least two terraces are almost everywhere present.

Relations to the Dresbach formation.—There is apparent conformity between the Franconia and Dresbach formations; but the fact that there are some differences in the sequence at the top of the Dresbach and the presence at the top of that formation of what may be small erosion channels suggest that the contact of the two formations is one of disconformity, with the possibility that the lower was eroded before the deposition of the upper.

Subdivisions and their characteristics.—The greater portion of the Franconia formation consists of fine-grained quartz and glauconitic sandstones. The clay content is limited to thin shale partings. A few beds contain small percentages of dolomite and near the base there is a sandy limestone. There are few beds in the formation which do not contain some greensand.

The thickness of the Franconia varies from 120 to 173 feet. The thickest sections are in the northern halves of the two quadrangles, although a well drilled at Cashton, just off the southeast corner of the Sparta quadrangle, indicates a thickness of about 170 feet. The thinnest section, 120 feet, was measured near the center of the Sparta quadrangle.

It is possible to divide the Franconia formation into five members, which in ascending sequence are: (1) the basal sandstone and overlying calcareous layer, (2) the micaceous shale, (3) the lower greensand, (4) the yellow sandstone, and (5) the upper greensand. These five members are continuous over the whole of the two quadrangles and for considerable distances beyond their limits.

1. The basal sandstone is roughly and irregularly bedded and is everywhere cross-laminated. Colors vary from gray to brown with

some layers so rich in greensand as to have a greenish-black color. Sorting is extremely poor. Fossil fragments, of which every one appears to have been washed about for a considerable time before final deposition, are locally very abundant. The thickness varies from 1 to 6 feet.

The overlying calcareous layer varies from a calcareous sandstone to a nearly pure limestone. The rock has a brownish-pink to red color and is generally cross-laminated with short fore-sets to the laminations. These have no constant direction of inclination. Small articulate brachiopods are present locally in considerable abundance. The thickness varies from nothing to about 4 feet.

2. The micaceous shale is really a fine-grained, thin, laminated sandstone. The colors vary from gray to yellow. The sandstone is composed chiefly of quartz with some of the bedding and lamination planes containing an abundance of thin flakes of white and colorless mica. Some beds are current-ripple marked and others have the bedding planes abundantly covered with fucoidal markings. Fossils, all of which appear to have been washed about before deposition, are quite abundant. The thickness varies around 15 feet.

3. The lower greensand is composed of thin laminated glauconitic and quartz sandstones. Greensand is present in essentially every bed; the proportion varies widely. Some thin layers are fully 75 per cent greensand, many beds have more than 20 per cent, while in others its occurrence is limited to occasional grains. Some of the strata are evenly bedded, but more commonly the bedding is decidedly irregular and lenticular. Cross-lamination is present throughout. The fore-sets are generally short and apparently have no uniform direction of inclination. Near the middle are mud-cracked layers which have been seen in nearly every exposure of the member. Both wave and current ripple mark, the latter by far the more abundant, are present in every exposure of any size. Fossils, all of which appear to have been washed about before final deposition, are common in many beds. The thickness varies around 40 feet.

4. The yellow sandstone member is composed of thick-bedded, horizontal and cross-laminated yellow and gray sandstone. Greensand is present in some layers. Transverse worm tubes are the

only fossils which have been seen. The thickness varies from 40 to 50 feet.

5. The upper greensand is similar in its characteristics to the lower greensand, but fossils are not nearly so common. Near the top are thin layers (1 inch maximum thickness) of very dolomitic, fine-grained, yellow sandstone interbedded with highly glauconitic medium-grained sandstone. Iron pyrite has been observed locally. The thickness varies from 54 to 70 feet.

Conditions of origin.—The Franconia sediments are wholly of marine origin, a conclusion proved by the quite general abundance of marine fossils. The cross-lamination everywhere present shows that the deposition took place above wave-base. The much smaller dimensions of the grains of sand and the higher percentages of angular grains suggest that the waters were considerably deeper than were those in which the Dresbach sediments of these quadrangles were deposited. The mud cracks in the lower greensand prove that at times during the deposition of that member several hundred square miles of the two quadrangles lay above water-level. The writers believe that somewhat similar shore conditions obtained during Franconia time as during Dresbach, with the difference that the Franconia sediments were deposited somewhat farther from land influences. Any interpretation must take into consideration the occurrence and abundance of greensand. This evidence has not been thoroughly evaluated, but nothing has been discovered which is not in harmony with the foregoing interpretation.

THE ST. LAWRENCE FORMATION

The St. Lawrence formation was defined by N. H. Winchell as the St. Lawrence limestone.[1] Its limitations were not definitely given because they were not known. The stratigraphic boundaries as they exist in western Wisconsin were worked out by Ulrich, and in this article the term is used with the significance given it by him. The strata of the two quadrangles which are referred to the St. Lawrence by the writers were designated the Sparta shales by Shipton on the supposition that they represented an

[1] N. H. Winchell, *Minn. Geol. and Nat. Hist. Surv., Second Ann. Rept.* (1874), pp. 152–55; *Fourth Ann. Rept.* (1876), pp. 32–34.

undescribed stratigraphic unit.[1] This supposition does not appear to be correct.

Where the St. Lawrence is not overlain by higher strata there develops a rolling topography of gentle outlines. Where higher strata are present there is a gently sloping surface on which relatively resistant strata near the middle of the formation give rise to discontinuous terraces. Quite commonly the upper beds of the St. Lawrence form the basal portions of the higher tier of cliffs.

Relations to the Franconia formation.—At all places where the contact between the Franconia and the St. Lawrence has been seen there is present an edgewise conglomerate composed of pebbles derived from the upper greensand member of the Franconia. These pebbles appear to have been indurated before their deposition, thus indicating the exposure and erosion of Franconia rocks at the beginning of the St. Lawrence deposition. If such erosion has occurred, as appears quite probable, it follows that the two formations are separated by a disconformity. The variation in thickness of the Franconia is in harmony with this conclusion.

Characteristics.—In the exposures of the Tomah and Sparta quadrangles the St. Lawrence formation consists largely of sandstones. Some of the beds of the lower half are more or less dolomitic and shaley and others contain small quantities of greensand. Farther to the southeast in the Wisconsin Valley the dolomite content is greater, and one member of the formation is a dolomite.

It is possible to divide the St. Lawrence into two members: a lower, composed of shaley and fine-grained, light-yellow to light-brown sandstone in which there are some dolomitic layers with local lenses (1 foot maximum thickness) of gray- and purple-spotted dolomite and also a little greensand, and an upper, consisting of fine-grained yellow sandstones in which are several layers (6 inches to 4 feet) of conglomerate composed of fine-grained yellow sandstone pebbles of lenticular shapes in a matrix of yellow sandstone of coarser grain. The pebbles are commonly in horizontal position, but a conglomerate near the middle of the formation has them in edgewise position with inclinations varying to nearly vertical. The

[1] W. D. Shipton, "A New Stratigraphic Horizon in the Cambrian System of Wisconsin," *Proc. Iowa Acad. Sci.*, XXIII (1916), 142–45.

sandstones are generally thin-laminated and quite regularly bedded. In some of the layers, particularly those in the upper member, cross-lamination is present to a high degree. The angles of inclination are generally low and of variable direction; but inclinations of southerly direction appear to be the more common. The thickness varies from 78 to 110 feet.

Fossils are extremely abundant in some layers, most of them being trilobites. One of the locally developed dolomitic layers of the lower member contains numerous brachiopods which are identical with, or closely related to, *Billingsella coloradoensis* (Shumard). The broken condition of the trilobites indicates that they were washed about by waves and currents before their final deposition.

Conditions of origin.—The St. Lawrence strata are of marine origin, and the sediments composing them were deposited in shallow water. Some beds were deposited under conditions which permitted the development of mud cracks, such having been found near the base of the formation on the northeastern edge of the Tomah quadrangle and near the middle of the lower member on the Wisconsin River. The numerous bands of conglomerate prove waters sufficiently shallow for the transportation of good-sized pebbles over extensive areas; presumably these were derived from the shores and carried out to deeper waters. They may possibly indicate backward and forward migration of the shore line. It is believed that the broad sand-flat conditions postulated for the times of the preceding formations were still existent, and that the St. Lawrence sediments indicate somewhat greater depths of water and greater distances from land conditions than obtained during the deposition of the Dresbach sediments of the two quadrangles.

THE JORDAN FORMATION

Succeeding the fine-grained sandstones of the upper St. Lawrence are sandstones which are correlated with the Jordan formation of Minnesota, the writers using that term in the sense defined by Ulrich in the paper by Walcott. Throughout the two quadrangles the sandstones referred to this formation in large part make the upper tier of cliffs.

Relations to the St. Lawrence formation.—In many places it is extremely difficult to locate the surface of division between the St. Lawrence and Jordan formations. Locally the strata assigned to the Jordan begin with a long, fore-set, cross-laminated stratum which in comparison with the more horizontally laminated St. Lawrence makes the contact quite conspicuous. In some exposures a thin layer of conglomerate marks the contact. In their larger relations the two groups of rocks are quite different, the bedding of the Jordan being much more irregular and the sands more coarse than obtain in the St. Lawrence. The writers have observed no decisive evidence in this area that the St. Lawrence strata were eroded before the deposition of the Jordan.

Characteristics.—The Jordan formation in these two quadrangles consists wholly of sandstone. The textures vary from coarse to fine and the colors from gray to light brown. The sorting is generally not good. Some beds contain an abundance of fine-grained sandstone pebbles. A characteristic feature is the presence of calcareous concretions with diameters varying from a fraction of an inch to about 2 inches. The bedding is massive and extremely irregular. Cross-lamination and cross-bedding are present throughout, some of the fore-sets being up to 50 feet in length and having angles of inclination for such lengths up to 25°. Directions vary, but the writers' observations indicate a dominance of inclination in a southerly direction. No fossils have been observed in this formation in either of the two quadrangles. The thickness varies from about 20 to about 40 feet.

Conditions of origin.—There is no known evidence in either of the two quadrangles to indicate that the Jordan sandstone is of marine origin. Parts of it appear to have been deposited by the wind. To the writers it appears probable that the formation represents the emergent deposits consequent upon the complete withdrawal of the waters from the sand flats postulated for the times of the preceding formations.

THE MADISON (?) FORMATION

Overlying the sandstones which have been identified as belonging to the Jordan are other sandstones which in some respects resemble those of the Madison formation. These sandstones are

better stratified than are those immediately below. They are also usually more or less dolomitic, and at or near the top there is quite generally a hard quartzite-like sandstone to which the field name of "clinkstone" was given. Up to the present these sandstones have yielded no fossils other than worm borings which resemble those found in the typical Madison sandstone. The thickness varies from 2 to about 20 feet.

If these sandstones are really of Madison age it is probable that an erosion interval occurred between the deposition of the Jordan and the Madison. The decisive evidence for such an interval has not been found in these quadrangles, although suggested by the considerable variation in the thickness of the Jordan. Such variation in thickness, however, is readily explained through inequality of deposition, which is a rather usual condition in sandstone deposits. Near Madison the Mendota dolomite is said by Ulrich to hold a stratigraphic position between the Madison and Jordan formations.[1] If this be correct and these sandstones are really of Madison age, there is little doubt of the presence of a disconformity.

ORDOVICIAN SYSTEM

INTRODUCTION

Only two formations of the Ordovician system are present within the two quadrangles. These are the Oneota dolomite (in the arrangement of the systems of Dr. Ulrich the Oneota and the Madison are referred to his Ozarkian system) and the St. Peter sandstone, each markedly different from the other in character, origin, and distribution. The two formations are separated from each other by a decided disconformity of marked relief.

THE ONEOTA FORMATION

The Oneota formation underlies the higher uplands and, except for small outliers, is largely confined to the southern halves of the two quadrangles. These upland areas have gentle outlines and slope with slight inclination in a southwesterly direction.

[1] E. O. Ulrich, "Correlations by Displacements of the Strandline, etc.," *Bull. Geol. Soc. Amer.*, XXVII (1916), 460.

The Oneota is quite commonly considered the lower member of the Prairie du Chien formation. In the older nomenclature it constituted one of the members of the Lower Magnesian group.

Relations to underlying strata.—There is essential parallelism between the beds of the Oneota and underlying strata, but it is believed that the latter were eroded before the deposition of the former. The basal bed of the Oneota is quite commonly a conglomerate, and mud cracking is not rare in the associated clayey beds. The quartzite-like beds—the "clinkstones"—in the upper portion of the Madison (?) may be a case of pre-Oneota case-hardening resulting from exposure before Oneota deposition. Near Madison bowlders of a quite similar quartzite are present in the basal Oneota, suggesting that the foregoing is a possibility. The thickness of the underlying sandstones varies from place to place, and the upper surface of these sandstones suggests erosion before the deposition of the Oneota.

Characteristics.—The Oneota formation consists of firm and compact dolomites in regular beds. Colors vary from gray to drab. Some of the lower beds are oölitic. The basal beds are somewhat sandy, and a conglomerate of dolomite and sandstone pebbles in a sandy dolomite matrix is quite commonly present at the base. This conglomerate and some of the immediately overlying sandstone beds contain flakes of green shale. The sandy beds persist through about a dozen feet of strata. Quite commonly the sandy beds are so firmly cemented as to form quartzite. A few feet above the base there is a rather persistent bed of fine-grained white sandstone which locally is firmly cemented to form a white quartzite. Much gray, blue, and yellow chert is present throughout, and some beds contain vast quantities. The chert of the oölitic layers is also oölitic. The dolomite contains many small cavities, some of which are lined with white, yellow, and amethystine quartz.

The maximum thickness of the Oneota in these areas is not believed to exceed 170 feet.

The most common fossils of the Oneota formation are irregular masses of *Cryptozoa*. These are abundantly present as isolated individuals and more rarely as reeflike masses, one of the latter

quite commonly being present about 30 feet above the base.. In fully half of the occurrences they are composed of chert. Other common fossils are small cephalopods, low-spired gastropods, and shells of a chiton-like organism. These are generally poorly preserved, casts and molds being the only forms which have been observed, and the writers—the chiton-like form excepted—have found them only in the chert. The writers have found no fossils composed of dolomite except those of *Cryptozoa*.

Conditions of origin.—The strata of the Oneota formation are wholly of marine origin. They are not the deposits of deep water, but in large part appear to have been deposited below wave-base.

THE ST. PETER FORMATION

The St. Peter sandstone occurs only as small patches which fill erosion depressions in the Oneota. None has been discovered over the northern half of the area. The most extensive occurrence is in the southeastern corner of the Sparta and the adjacent part of the Tomah quadrangle. Residual float from the St. Peter is quite abundantly present over those parts of the uplands which are underlain by the Oneota.

Relations to underlying formations.—The most striking feature of the St. Peter formation is the relief of the disconformity which marks its base. The stratigraphic position of the St. Peter in this region is above the Shakopee formation; but that formation, if deposited over these two quadrangles, was removed before St. Peter deposition, so that the St. Peter rests on the Oneota, except in one exposure, where it was found to rest on the Jordan, thus giving to the surface of disconformity a stratigraphic relief of fully 200 feet.

Characteristics.—The St. Peter formation consists of loose, friable, yellow to brown, fine- to medium-grained sandstone with a variable thickness of red and green non-calcareous shales and fine-grained shaley yellow sandstones in the basal portions. At every place where the base of the stratified St. Peter was observed it rests on a residuum of red clay and chert which is altogether without stratification. This residuum was derived from the weathering of the Oneota and possibly higher formations. In this article this unstratified material is assigned to the St. Peter, although it developed during the time of erosion which intervened in this area

between the Oneota and the St. Peter and thus might be considered a distinct formation. Some of the sandstones are locally so case-hardened as to resemble quartzite, and these form a residual float over the surface of the Oneota. In many cases the sandstones are so little cemented as to be quarried for sand. Except for the basal layers, the sands are clean, well sorted, and well rounded. A large proportion of the grains are of high sphericity. The strata immediately above the residuum are fairly well bedded. Higher strata have all degrees of cross-lamination and cross-bedding.

The known thickness of the St. Peter in this area does not exceed 70 feet. No fossils have been found in the St. Peter sandstones of this area or, for that matter, in any part of Wisconsin known to the writers. In eastern Minnesota the St. Peter has yielded fossils.[1]

Conditions of origin.—While all the facts relating to the origin of the St. Peter have not yet been completely evaluated and more data are being collected, it does not appear probable to the writers that any part of the St. Peter sandstones in either of the two quadrangles is of marine origin. The basal portions are certainly of residual origin and as this residuum extends over the tops of the St. Peter hills it proves the absence of marine-wave wash during the deposition of all material up to the tops of these hills. The shales and sandstones immediately overlying the basal residuum appear to be of stream deposition. The higher, clean, cross-laminated sands have characteristics which suggest their modification and deposition by the wind.

CONCLUSION

With the St. Peter formation the Paleozoic section of the Sparta and Tomah quadrangles is concluded. That other Ordovician and also Silurian formations once extended over this region is strongly suggested, if not proved, by the ragged edges of strata of these two systems which are found at comparatively short distances to the south and west. It is possible that formations younger than the Silurian were once present; but, if so, evidence of their former existence has not been discovered.

[1] F. W. Sardeson, *Bull. Minn. Acad. Nat. Sci.*, IV, No. 1 (1896), pp. 64–88.

THE HORIZON OF THE MARINE JURASSIC OF UTAH

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Some time ago the writer, during the course of a reconnaissance in southern Utah, made a small collection of fossils from marine beds near the base of what is quite probably the McElmo formation. These were collected about a half-mile southwest of Teasdale (Teardale on the Fish Lake reconnaissance topographic sheet of the United States Geological Survey), probably in section 20,

Fig. 1.—Contact of thin-bedded marine Jurassic limestone on white cross-bedded sandstone of La Plata group. One-half mile southwest of Teasdale, Utah. (Contact at black line.)

T. 29 S., R. 4 E. At the point where the fossils were collected the exposures consisted of about 100 feet of white massive cross-bedded sandstone, taken to be the top of the La Plata, above which were a few feet of thin-bedded shaly limestones, constituting the fossil-bearing horizon (Fig. 1). On account of the inaccessibility of the slopes and the very limited time available, no detailed section was measured at this point.

The writer, however, measured a detailed section near the mouth of Cedar Canyon, about 6 miles due east of Loa, along the west base of Thousand Lake Mountain, just east of the fault that is reported by Dutton[1] to form the west scarp of that mountain. The section follows. Figure 2 shows the beds in the upper part of the section.

SECTION AT MOUTH OF CEDAR CANYON, 6 MILES EAST OF LOA

No.	Feet	
29	....	Talus from cliffs of overlying lava.
28	375+	Alternating green and red sandy shales with occasional gypsum beds.
27	40	Covered slope, abundant gypsum fragments, probably gypsum.
26	100	Gypsum with thin clay seams.
25	10	Drab shale, more massive than No. 24, forms ledge.
24	22	Thin-bedded drab shale in slope.
23	50	Calcareous gray shale, in cliff, weathers with rounded surfaces.
22	3	Slightly argillaceous notably cross-bedded limestone.
21	11	Covered slope; digging shows red and gray clay.
20	5	Dense thin-bedded calcareous shale or argillaceous limestone, forms bench.
19	32	Thin-bedded calcareous shale or argillaceous limestone, forms slopes.
18	1	Brown, sandy, porous limestone.
17	4	Greenish gypsum.
16	5	Green argillaceous sandstone.
15	5	Covered slope.
14	30	Gypsum.
13	25	Covered slope, probably red shale.
12	1	Gray limestone.
11	3	Thin-bedded drab shale.
10	5	Very light gray limestone.
9	16	Fairly well-bedded greenish, argillaceous sandstone.
8	10	Covered, probably shale.
7	20	Fissile red-brown shale, in a bench with marked re-entrant angles.
6	36	Thin-bedded drab shale.
5	6	Gray limestone, with thin shale near middle, fossiliferous.
4	1	Greenish sandy shale.
3	8	Thin-bedded drab limestone, slightly cross-bedded.
2	35	Tan-colored, well-bedded argillaceous sandstone.
1	130	White cross-bedded sandstone.
	989	

[1] C. E. Dutton, "Report on the Geology of the High Plateaus of Utah," 1880.

In this section, Nos. 1 and probably 2 are thought to be La Plata. No. 6 is almost certainly the same horizon from which the Teasdale collection of fossils was made. It is perhaps 10 miles or less from Cedar Canyon southeast to Teasdale.

The fossils were submitted to Dr. T. W. Stanton, of the United States Geological Survey, who lists them as follows: *Pentacrinus whitei* Clark; *Camptonectes platessiformis* White; *Trigonia quadrangularis* Hall and Whitfield; small undescribed gastropods.

Dr. Stanton[1] says, "These fossils show close relationship with the Sundance fauna, but there have been different opinions concerning the exact position of the bed containing them with reference

Fig. 2.—White, red, and green sandy shale and gypsum above marine Jurassic limestone, head of Cedar Canyon, 6 miles east of Loa, on west slope of Thousand Lake Mountain, Utah.

to the La Plata. C. T. Lupton, who observed the same fossiliferous horizon, included it in the McElmo and agreed with you in considering the top of the underlying sandstone as the top of the La Plata.[2] W. B. Emery, who has had the advantage of field work in northeastern Arizona and northwestern New Mexico as well as southern Utah, thinks that this fossiliferous Jurassic limestone represents the Todilto formation which is near the middle of the La Plata group according to Gregory's stratigraphy in *Professional Paper 93*.

[1] Personal communication.

[2] *U.S. Geol. Surv., Bull. 541*, p. 125.

You will find his discussion of the section in a paper on the Green River Desert section, Utah."[1]

The earliest reference to fossiliferous beds at this horizon in this locality that has come under the notice of the writer is by Gilbert,[2] who, in describing the Flaming Gorge formation, says: "In the immediate vicinity of the Henry Mountains it varies little except in color from summit to base, but in other localities not far distant it is interrupted near the base by thick beds of gypsum and gypsiferous clays, and by a sectile, fossiliferous limestone." Gilbert's Vermilion Cliff and Gray Cliff sandstones in this locality have been generally supposed to represent the two major divisions of the La Plata group, described by Gregory[3] in the Navajo country as the Wingate and Navajo sandstones respectively; and although Cross[4] interprets the Vermilion Cliff of the older writers to be the upper part, at least, of the present Dolores formation, anyone who has studied the detailed section given by Gilbert in the identical localities from which he describes them cannot help being certain that his upper Shinarump shales are Dolores, and that his Vermilion Cliff sandstone includes the base of the La Plata and probably does not include any of the Dolores. Likewise Gilbert's Gray Cliff is La Plata, and his Flaming Gorge is in part, and probably in totality, the equivalent of the McElmo formation of more recent writers.

The present writer has studied these formations in some detail in the region described by Gilbert, particularly along Water Pocket Canyon and on the Water Pocket Flexure. Here the total thickness of the Vermilion Cliff and Gray Cliff together is estimated (not measured) as not less than 1,500 feet. Near the contact between them is about 100 feet of shaly red sandstone, less resistant than the material above and below, and this is believed by the writer to correspond to Gregory's Todilto beds. The general

[1] *Amer. Jour. Sci.*, XLVI (October, 1918), 551–57.

[2] G. K. Gilbert, *Report on the Geology of the Henry Mountains*, 1880.

[3] H. E. Gregory, "Geology of the Navajo Country," *U.S. Geol. Surv., Prof. Paper 93*, 1917.

[4] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Jour. Geol.*, XV (1907), 634–79.

nature of these beds is best brought out by the illustrations. Figure 3 shows a sheer wall of the Vermilion Cliff; Figure 4 illustrates one of the characteristic arches developed by the curved lamination of the same formation, and, in addition, shows the overlying thin, shaly red sandstones of the supposed Todilto. In Figure 5 the same thin-bedded red sandstone is shown at the base, capped by a remarkable wall of the upper, or Gray Cliff, formation. In the foreground of Figure 6 is shown a low cliff of the Moenkopi capped with Shinarump conglomerate; above that, slopes exposing 500 to 600 feet of Dolores or Chinle shales (upper Shinarump shale); in the middle distance massive cliffs of the lower La Plata or Vermilion (Wingate?); next above are slightly thinner beds capping the cliff (probably Todilto); and finally in the background the amazing domes of the upper La Plata or Gray Cliff (Navajo?), which give the name of Capitol Wash to the canyon. Figure 7 also shows the three divisions of the La Plata here, the Vermilion Cliff below (the sheer wall), then the more shaly beds, and finally the Gray Cliff sandstone above with its characteristic domes.

FIG. 3.—Cliff of basal La Plata sandstone (Vermilion Cliff), in Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah. (Vertical lines are not bedding, but probably water streaking.)

Near the base of the Flaming Gorge at this point are also massive tan sandstones identical with the La Plata (Figs. 8, 9, 10) and only distinguished from it by their position well above both divisions of the La Plata, as just described. In Water Pocket

Canyon the basal Flaming Gorge contains heavy gypsum beds occupying a position below this tan sandstone and above the twofold La Plata sandstones. In this locality the fossiliferous limestones were not noted by the writer, but they are reported by Gilbert[1] west of Masuk Plateau. The localities in Water Pocket Canyon are perhaps 30 or 40 miles southeast of where the Teasdale collection was made.

In the Water Pocket Canyon locality the Flaming Gorge beds supposed to be McElmo are directly overlain by sandstones that

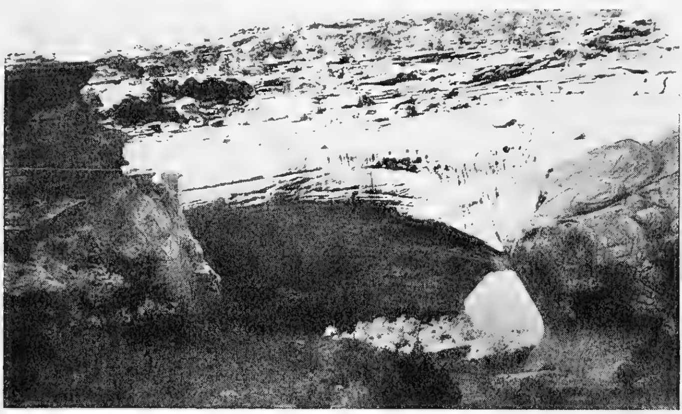

FIG. 4.—Lower La Plata (Vermilion Cliff) sandstone, with characteristic arch, overlain by thin-bedded red sandy shale (Todilto?) in Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah.

grade up into typical Mancos shale. From these sandstone beds the writer collected the following fossils along Bitter Creek Divide. Identifications were made by Dr. Stanton, who says:[2] "The collection from the sandstone near base of Mancos shale in Water Pocket Canyon yielded a number of species that are known to be characteristic of the sandstones in the lower part of the Mancos, as follows: *Ostrea prudentia* White; *Exogyra columbella* Meek; *Exogyra sp.*, related to *E. laeviuscula* Roemer;* *Exogyra sp.*, related to *E. ponderosa* Roemer;* *Gryphaea newberryi* Stanton;

[1] G. K. Gilbert, *op. cit.*, Fig. 2. [2] Personal communication.

*"White identified these two Texas species in collections from southeastern Utah and I repeated his descriptions and figures under the same names in *Bull. 106* but I now think them to be probably distinct."

Plicatula hydrotheca White; *Camptonectes platessa* White; *Astarte? sp.; Cardium trite* White; *Liopistha (Psilomya) elongata* Stanton."

This should serve to fix the Flaming Gorge, which is next below these sandstones, as at least in part McElmo, and the writer has shown, in the foregoing, that it lies above a sandstone with two definite divisions, believed to correspond to the La Plata.

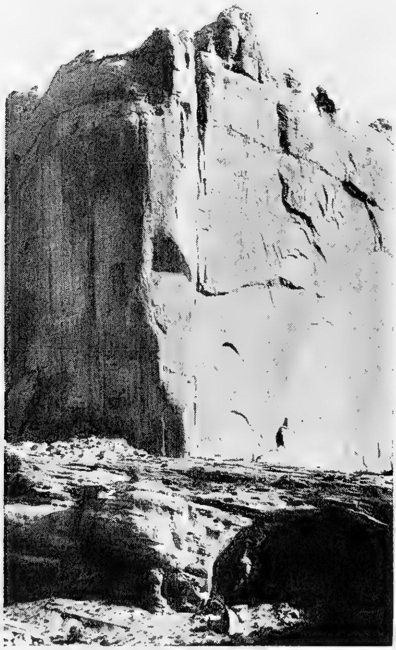

FIG. 5.—Thin-bedded red sandy shale (Todilto?) capped with La Plata (Gray Cliff) sandstone, Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah.

Unfortunately, at the point where the fossils were collected, the relations so plain in Water Pocket Canyon could not be seen, partly because of faulting and partly because of burial by lavas. However, there is but little doubt in the writer's mind that the Jurassic fossils were found in beds below typical McElmo and above the top of the La Plata. He believes that the McElmo formation is in its upper part equivalent to the Morrison, and that the lower beds, apparently equivalent to the Sundance of Wyoming, lie above the top of the true La Plata (Table I).

This is in marked contrast to the conclusions of Emery,[1] who considers that the Gray and Vermilion Cliff sandstones are both Wingate, that the fossiliferous gypsum-bearing beds of the writer's section are Todilto (middle La Plata), and that the sandstones placed in the McElmo by the writer are Navajo. As near as the writer can judge, Emery's chief reason for so believing is the lithologic similarity of the limestones of the type Todilto

[1] W. B. Emery, "The Green River Desert Section, Utah," *Amer. Jour. of Sci.*, XLVI (1918), 551–77.

CORRELATION TABLE*

Age	Gregory Navajo Country	Gilbert Henry Mountains†	Dake Present Paper	Emery Green River Desert	Cross Intepretation of Powell	Lupton Green River Oil Field
Cretaceous	Dakota sandstone	Henry's Fork group (in part)	Dakota (locally absent)	Dakota	Dakota	Dakota
Lower Cretaceous or Jurassic	McElmo formation	Flaming Gorge group	McElmo Group: Upper McElmo	Upper McElmo	Flaming Gorge group	Upper McElmo
			McElmo Group: Salt Wash member	Salt Wash member		Salt Wash member
			McElmo Group: Lower McElmo (Sundance ?)	La Plata Group: Navajo sandstone‡		Lower McElmo
				La Plata Group: Todilto formation		
Jurassic	La Plata Group: Navajo sandstone	Gray Cliff sandstone	La Plata Group: Navajo sandstone	La Plata Group: Wingate sandstone	White Cliff sandstone	La Plata sandstone
	La Plata Group: Toldito formation	present, not differentiated	La Plata Group: Todilto shaly sandstone			
	La Plata Group: Wingate sandstone	Vermilion Cliff sandstone	La Plata Group: Wingate sandstone			
Triassic	Chinle formation	Shinarump Group: Shinarump division "a"	Dolores formation	Chinle formation	Vermilion Cliff	
					Shinarump Group: Upper Shinarump (Dolores)§	
	Shinarump conglomerate	Shinarump Group: Shinarump conglomerate	Shinarump conglomerate	Shinarump conglomerate	Shinarump Group: Shinarump conglomerate	
Permian (?)	DeChelly sandstone	Shinarump Group: Shinarump division "c"	Moenkopi	Absent	Shinarump Group: Lower Shinarump (Moenkopi)	
	Moenkopi			Moenkopi		
Pennsylvanian	Undifferentiated Pennsylvanian	Aubrey group	Kaibab limestone	Pennsylvanian (?)	Aubrey group	
			Coconino sandstone			

* Dotted lines indicate reported unconformities.
† Gilbert classes all formations between the Aubrey group and the Henry's Fork conglomerate as Jura-trias.
‡ Todilto and Navajo, as recognized by Emery, are considered by him to be Jurassic.
§ Powell classed the entire Shinarump group as Triassic.

with the fossiliferous horizons here described, and the fact that the Todilto seems to be thickening to the northwest from the type area.

FIG. 6—Looking into Capitol Wash, on road between Fruita and Notom, Utah. (M=Moenkopi, S=Shinarump, D=Dolores, W=La Plata [Wingate? or Vermilion Cliff], T=La Plata [Todilto?], N=La Plata [Navajo? or Gray Cliff]).

FIG. 7.—Dirty Devil Canyon, Fruita, Utah. Slope at base is Dolores, and the cliffs show three divisions of the La Plata.

Lee[1] comes to conclusions identical with those of Emery and cites many instances in southern Colorado and northern New

[1] W. T. Lee, "Early Mesozoic Physiography of the Southern Rocky Mountains," *Smithsonian Misc. Coll.*, LXIX, No. 4 (1918).

Mexico of the occurrence of limestones and gypsum above a sandstone which he calls repeatedly lower La Plata, or Wingate. The limestones and gypsum are correlated by him with the Todilto or

FIG 8.—Flaming Gorge (McElmo?) in Water Pocket Canyon, near Henry Mountains, Utah. The knobs of sandstone in the foreground overlie gypsum beds and are part of what Emery correlates as Navajo.

Photo by L. J. Zoller

FIG. 9.—Detail of sandstone beds of McElmo shown in Fig. 8 above

middle La Plata. In many of the sections referred to by Lee no sandstone at all is mentioned above the limestones and gypsum. In a few an overlying sandstone is described as probably upper La Plata or Navajo, but at no point does it seem, from his descriptions, to closely resemble typical Navajo.

The writer opposes the conclusions of Emery and Lee on the following grounds:

1. There are, at several other horizons in the La Plata, limestone lenses of character almost absolutely similar to the Todilto with which, on lithologic grounds alone, these fossiliferous beds might quite as well be correlated.

2. The limestones of the Todilto and all the other limestones of the La Plata are apparently absolutely non-fossiliferous, while these beds are packed with fossils.

3. As described by Gregory the Todilto is not a gypsum-bearing formation. On the other hand, the McElmo, where

Photo by L. J. Zoller

FIG. 10.—McElmo gypsiferous sandstone and shale, Water Pocket Canyon, Utah. These beds lie above the gypsum beds in dispute, and are considered Navajo by Emery.

definitely known to overlie true Navajo, though it does not carry gypsum beds, is repeatedly reported as highly gypsiferous. Gypsum is also an abundant constituent of the fossiliferous series in question. In a personal letter Dr. Stanton called the writer's attention to the fact that the section in question differed from typical McElmo in its numerous gypsum beds. The criticism applies even more positively in comparisons with the non-gypsiferous Todilto. If, as Lee suggests, the Todilto represents the fringe of the marine fossiliferous beds, along embayments where conditions were unfavorable to marine life, the gypsum-forming conditions should surely be presumed to persist into the Todilto area, a feature of the Todilto that Gregory does not mention.

4. That portion of the Flaming Gorge described by Emery as the Navajo is lithologically very unlike the type Navajo. Among these dissimilarities may be mentioned the presence of much shale and considerable gypsum in the Navajo as described by Emery, and their conspicuous absence in the Navajo of Gregory. Furthermore, Gregory describes much limestone as an almost universal characteristic near the top of the Navajo sandstone in its type region. The Navajo of Emery is apparently quite without such limestones.

5. According to Gregory, greenish tints prevail in the base of the McElmo. The basal part of the section measured by the writer also shows many greenish beds.

6. In the section measured by the writer, totaling 989 feet, in which only the lower 165 feet are clearly La Plata, there are 824 feet of beds, among which it is almost impossible to draw any boundary. They are certainly not all Todilto, or else the Todilto has thickened most enormously in this section. If they are in part Navajo, as must be the case, under Emery's conclusion, then the Navajo here grades inseparably into Todilto.

7. The McElmo, in Gregory's report, is described as extremely variable, but as prevailing sandy, with many intricately cross-bedded sandstone members, a description which fits well the characteristics of the supposed Navajo of Emery's paper.

8. If the basal part of the Flaming Gorge be considered as Todilto and Navajo, the total thickness of the La Plata group in the Water Pocket Canyon region will approximate 2,500 feet, which represents at least unusual thickening of the formation.

9. The old original classification by Gilbert represents a group of lithologic units with much more natural physical boundaries, at least in the area studied by the writer, than do those presented by Emery. In justice it must be said, however, that the writer has not seen the localities described in Emery's paper. His own section was measured about midway between the area studied by Emery and the Water Pocket Canyon, and he has studied the formations south but not north of that point.

10. The gypsiferous beds of northern New Mexico, so frequently mentioned by Lee, do not appear to be overlain by any beds that

can with confidence be referred to the Navajo. The sandy beds which he describes as occurring above the gypsum fit more closely Gregory's description of the sandstones above typical Navajo, being those considered by Gregory to constitute the McElmo. This discrepancy could be brought about either by a mistake in the identity of the sandstones called Wingate below the gypsum beds, or by the absence of any true Navajo, which condition would allow the gypsum beds at the base of the McElmo to rest directly on Wingate or Todilto.

From an extensive personal survey of these formations over a region that includes the Water Pocket Canyon, Dirty Devil Canyon, the Moab Valley, the Big Indian Uplift, the San Juan Uplift, the Fort Defiance Uplift, and the Zuni Uplift, the writer is reasonably familiar with the lithologic variations of these formations, and in view of the facts presented he is forced to the conclusion that these marine Jurassic beds are not the equivalent of the Todilto, but that they are above the Navajo sandstone.

Whether or not they are a part of the true McElmo is another matter. The writer is quite in accord with Emery in believing that a pronounced break occurs at the base of the Salt Wash conglomeratic sandstone. A similar break, with heavy conglomeratic beds, was noted by the writer at the Sundance-Morrison contact in the valley of the south fork of Shoshone River, Wyoming. The following is quoted from the unpublished manuscript of a bulletin on that region prepared by the writer for the Wyoming State Geological Survey: "At several points, particularly near the southeast corner of section 19, T. 51 N., R. 103 W., there lies between typical Sundance and typical Morrison from 5 to 20 feet of coarse pebbly sandstone. The pebbles are all small, mostly less than one-fourth inch in diameter, and consist of gray shale, gray sandstone, black chert, and quartz, mostly well worn and rounded." A break at this horizon, of great importance, is considered probable by Schuchert.[1]

This break, if sufficiently widespread, might well justify the separation of the beds below the Salt Wash member as a distinct formation, equivalent to the Sundance.

[1] Charles Schuchert, "Age of the American Morrison and East African Tendaguru Formations," *Bull Geol. Soc. America*, XXIX (1918), 245–80.

THE WEST POINT, TEXAS, SALT DOME FREESTONE COUNTY

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INTRODUCTION

The West Point salt dome is a large, symmetrical structure of the salt-dome type occurring in the extreme southeastern corner of Freestone County, Texas. This dome structure is one of the most symmetrical and best defined, both geologically and topographically, of the North American salt domes, notwithstanding which it seems largely to have escaped the attention of geologists to the present time.

References to it in geologic literature are few and scant and no detailed description has yet been published. Deussen[1] referred to a dome in Freestone County as one of the inner belt of coastal domes, and Woodruff [2] first described the West Point dome generally, emphasizing particularly its fitness for study as a type example of salt-dome structure. Hopkins[3] included this dome, which he calls the Butler dome, on his index map showing the location of the Palestine dome, and Dumble[4] described it briefly under the same name.

The dome has been examined several times as a salt or petroleum prospect. Lee Hager reported upon it in 1908 and in his report mentions having examined it for private interests in 1907. Lewis C. Chapman reported on it in 1915 and various geologists of the

[1] Alexander Deussen, "The Humble, Texas, Oil Field," *Southwestern Assn. Pet. Geol., Bull. 1* (1917), pp. 60–79.

[2] In discussion of Deussen's paper. *Southwestern Assn. Pet. Geol., Bull. 1* (1917), pp. 79–84.,

[3] Oliver B. Hopkins, "The Palestine Salt Dome, Anderson County, Texas," *U. S. Geol. Survey, Bull. 661g* (1917).

[4] E. T. Dumble, "Origin of the Texas Domes," *Amer. Inst. Min. Eng., Bull. 138* (June, 1918), pp. 1629–36.

Roxana Petroleum Company made a very careful and detailed geologic and topographic map of the dome about the same time.

The writer visited the West Point dome in 1916 with Lewis C. Chapman. He was so struck by the symmetry of the dome, the clear manner in which its structure is revealed, and its peculiar and characteristic topography that he resolved to study it more

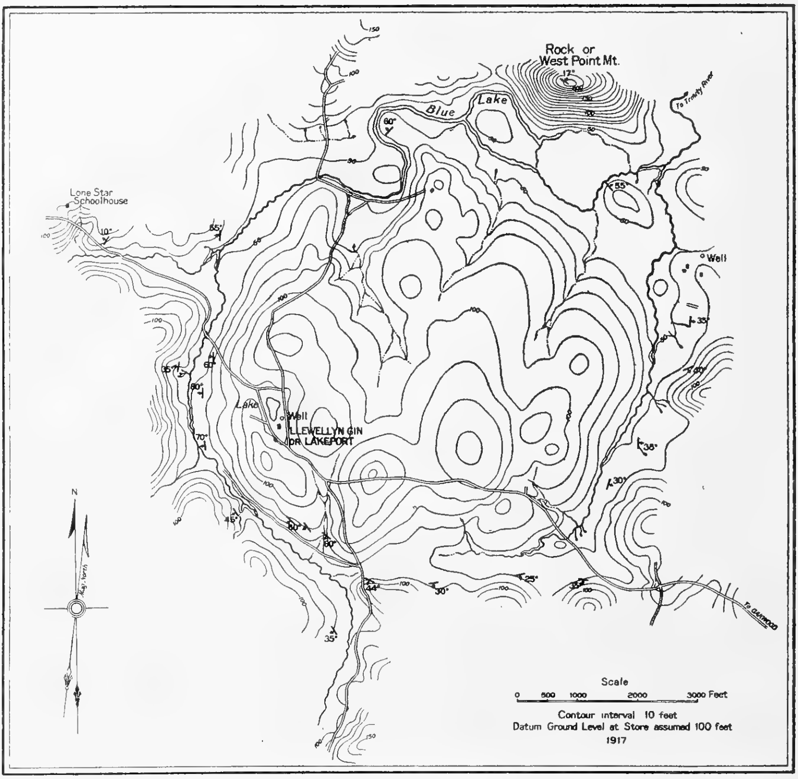

FIG. 1.—Topographic and geologic map of the West Point salt dome, Freestone County, Texas.

closely at the first opportunity as a type of salt-dome structure. This opportunity presented itself in November, 1917, and some five days were spent in making a rapid plane-table sketch of the dome.

The accompanying map (Fig. 1) is a result of this survey. Not enough time was available to make the detailed and extensive map which would better express fully the geology of the dome. Traverses

were run along the principal roads, around the circular drainage, and across the mound.

An attempt was made to express the drainage exactly, the essential topography, and sufficient dips and strikes to outline the dome structure. Many dip and strike observations could have been made in addition to those recorded. No attempt was made to map all of the springs and water seepages. A complete map of the dome should express in greater detail the topography outside of the circular strike drainage.

The writer has withheld this map in the hope of being able to make further field studies, but as the opportunity for such work seems remote, he offers the map in its present form as a contribution to the geology of salt domes. Acknowledgment is due and gratefully rendered to Earle S. Porter for his assistance in mapping the dome, to Lewis C. Chapman for much information regarding the dome, and to Sidney Powers, whose sketch and notes regarding a part of the dome the writer has seen.

LOCATION

The West Point salt dome lies some five to seven miles north of the town of Oakwood on the International and Great Northern Railroad, and extends from a mile or two east of Butler post-office to the western edge of the flood plain of the Trinity River (Fig. 2).

It is the southernmost known dome of the interior group of salt domes and forms a triangle with the nearby Palestine dome, the center of which lies some 9 miles N. 51° E., and with the Keechi dome, the center of which lies some 14.7 miles N. 34° E. from the center of the West Point dome. The remaining known domes of the interior group in Texas are the Brooks dome, some 39 miles N. 34° E.; the Steen dome, some 69 miles N. 27° E.; and Grand Saline, some 74 miles N. 9° E.

It will be noticed that West Point, Keechi, and the Brooks dome lie on a straight line striking N. 34° E. The Palestine and Steen domes lie near this line. This line of strike is roughly parallel to that of the Balcones fault, which strikes N. 25–30° E., and is some 70 miles distant, as well as roughly parallel to the belts formed by the outcrop of various Tertiary formations to the westward.

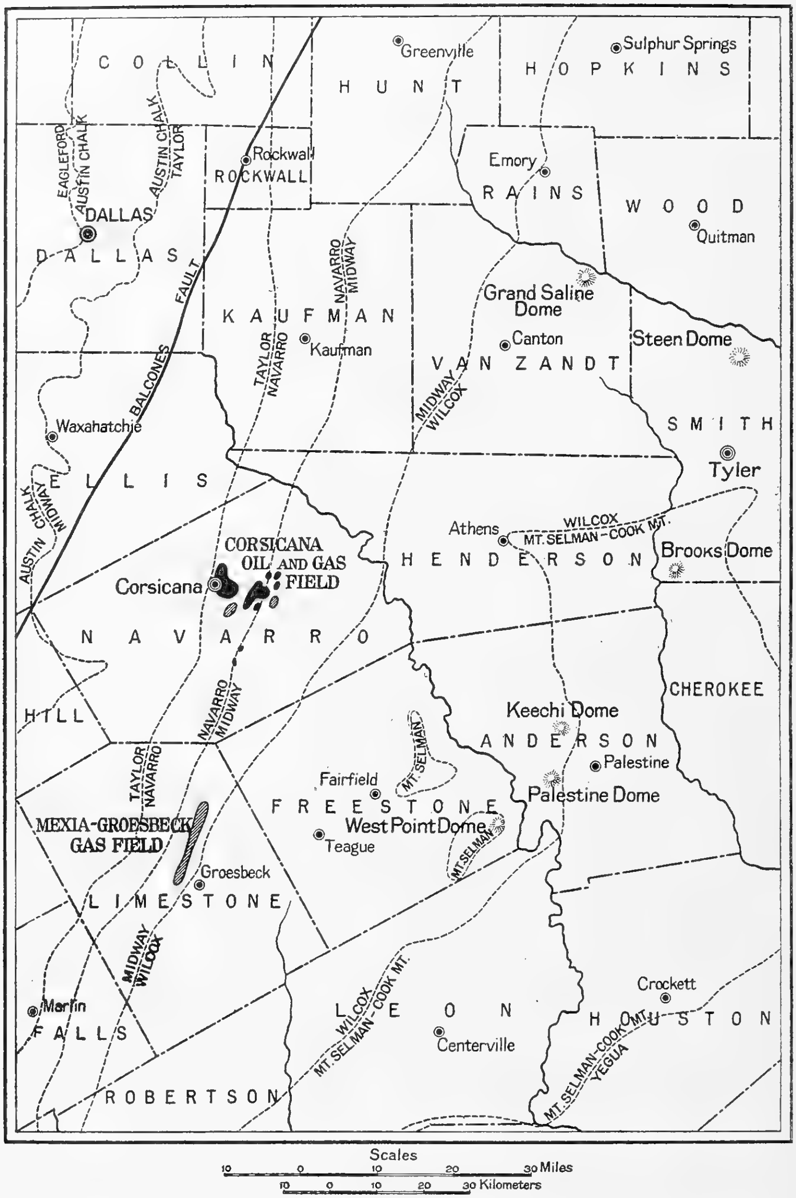

FIG. 2.—Index map showing location and relations of the West Point dome

This alignment and parallelism were recognized and mapped by Veatch[1] before he was aware of the existence of the Keechi and West Point domes.

Davis Hill, in Liberty County, some 110 miles S.SE., is the nearest of the known coastal salt domes, and the so-called Brenham dome is about the same distance S.SW.

The Batson and Saratoga fields, some 125 miles S.SE. from West Point, are the nearest proven oil fields with salt-dome structure. The nearest producing oil field of any type is the Powell pool of the Corsicana field, some 40 miles northwest, and the nearest producing gas field is the Mexia-Groesbeck field, some 37 miles due west of the West Point dome.

TOPOGRAPHY

Topographically, this dome consists essentially of an almost perfect circular mound surrounded by a ring-shaped valley, and this in turn is bounded on its outer margin by high hills having steep scarp faces toward the valley and long dip slopes away from it. This topography is so expressive that one would be justified in classifying this as a salt-dome structure on the basis of topographic evidence alone.

The mound forms in plane section an almost perfect circle 7,500 feet in diameter. The highest point is near its southern edge just opposite the divide between the two streams forming the ring-shaped encircling valley. The height of the mound here is sixty feet above that of the divide and one hundred feet above that of the junction of the two streams, the lowest point in the ring-shaped valley.

The mound is rather flat on top and dips steeply off to the valley on all sides, indicating that the erosion of the dome itself is not keeping pace with the cutting down of the valley. The erosion of this dome is developing regularly by means of channels and run-off normal to the major drainage, that of the ring-shaped valley. The longest draws or arroyos are those normal to the major drainage at its lowest point, and there seems to be no development

[1] A. C. Veatch, "The Salines of North Louisiana," *Geol. Survey Louisiana, Report of 1902*, pp. 41–100.

of laterals paralleling the ring-shaped drainage. This may be the result of the steep gradient of the draws and the softness of the Wilcox formation which covers the top of the mound, but it may also indicate that the beds on the top of the dome are not dipping so steeply as around its perimeter and consequently there is no tendency for strike drainage to develop.

The most striking feature of the topography is the comparatively broad ring-shaped valley which encircles the mound. This ring-shaped valley widens to a broad crescent-shaped area in its northeastern quadrant where the streams forming it come together and, passing through a gap just east of West Point Mountain, meander across the broad flood plain of the Trinity River to join it a short distance away.

The circular shape of this valley is due to the fact that streams forming have developed along the circular strike of the rocks around the salt dome or have been adjusted to it.

The principal stream is the one which comes into the dome at a point S.SE. of Llewellyn Gin, flows around its west and north sides through Blue Lake and, after being joined by the smaller eastern stream, flows off to Trinity River through the gap near West Point Mountain.

The fact that the direction of this stream where it comes into the dome is toward the West Point Mountain gap, by which it ultimately leaves it, suggests that it may previously have flowed directly across the dome and that it was adjusted to its present position by the formation of the dome.

The present drainage courses also suggest that this stream may have once flowed around the east side of the dome instead of the west side, as at present. The divide between the two streams is so low as to be almost imperceptible at the present time, and the direction of the draw just west of the road south from the Gin suggests that it was originally a tributary to the eastern drainage. If this suggested stream piracy actually occurred, it was probably effected by a tributary to the stream coming into the dome from south of the Lone Star schoolhouse and caused by more rapid erosion of the western channel resulting from the greater number of tributaries coming into it.

There is a gap, through which it is possible that the drainage once left this dome, about one-fourth of a mile south of the West Point Mountain gap.

The broadening of this valley into the crescent-shaped area already mentioned and the formation of Blue Lake and the imperfect drainage systems leading from it are evidently due to the drainage channels working down the dip toward the point of outlet and the fact that they have apparently reached the base-level of the Trinity River.

This ring-shaped valley, both in its narrow and broader courses, is a barren, open, prairie-like area covered with a sort of coarse marsh grass and is quite conspicuous because of its peculiar form and because of the vistas which it affords in this more or less wooded region.

Throughout the entire course of the valley, though occurring for the most part on its outer edge, are numerous springs and boggy places formed by the seeping of water. These springs are mostly of fresh water except for the salts leached from the formations from which they rise and which often forms incrustations of salt around the springs.

These springs are evidently formed by artesian water collected by the normally southeastward-dipping sands of the Wilcox formation over the large areas where it outcrops to the westward and coming to the surface here where the Wilcox is turned sharply upward around the edge of the salt core of the dome. The rarer brine and sulphurous water springs, some of which are found just south of West Point Mountain, doubtless rise from greater depths through faulting around the perimeter of the salt core.

Some of the brine springs near West Point have been worked intermittently for salt since before the Civil War.

These artesian springs bring up fine-grained sand and clay and thus form mounds, some examples of which are several feet across. Woodruff[1] cites the mounds formed along this ring-shaped valley, particularly on its north side, as excellent examples of the small mounds which are so typical of coastal-plain topography.

The outer circle of hills is generally higher than the inner mound and the hilly area extends off to the south and west in the dissected

[1] E. G. Woodruff, *op. cit.*

uplands formed by the rather extensive outlier of Mount Selman beds. To the northeast they extend but a short distance before the flood plain of the Trinity River is reached.

Though no investigation was made to determine whether or not there are more circular strike-drainage channels concentric to the valley mentioned in this hilly region, the writer strongly suspects that such drainge exists.

SURFACE GEOLOGY

The oldest rocks outcropping in the West Point dome are apparently the greenish-yellow clays and shales outcropping in the segment of the inner edge of the central mound lying between the road leading south from Llewellyn Gin and that leading from the Gin to the Lone Star schoolhouse. On a lithologic basis and guided by the apparent relation of these shales to the Wilcox formation, one would refer them to the Midway (Eocene) or Navarro-Taylor (Cretaceous) formations.

Sidney Powers has collected fossils from these shales or a horizon immediately above them at points respectively 1,000 feet NW.W. and 1,500 feet S.W. of Llewellyn Gin, and their age as published elsewhere[1] has been determined by Dr. C. Wythe Cook and Dr. L. W. Stephenson, of the United States Geological Survey, as Lower Eocene, either Midway or Wilcox and Upper Cretaceous.

On these bases the shales are assigned tentatively to the Midway Eocene and Navarro Upper Cretaceous. Dumble's[2] statement that this dome gives the same section as the Palestine salt dome, in which the outcrops of all of the formations of the Gulf series of the Cretaceous have been recognized, is clearly in error. The writer has seen no evidence of the outcrop, other than that just stated, of any Cretaceous rocks in this dome.

The center of the dome is covered with the very heavy sandy soil so characteristic of the Wilcox formation. Though not exhaustively searched, no outcrop of the country rock was seen

[1] The writer is very much indebted to the kindness of Dr. Powers for permission to use, in the present paper, these fossil determinations which he is discussing in greater detail elsewhere.

[2] E. T. Dumble, *op. cit.*

except an imperfect outcrop of a heavy yellow sandstone in the road some 1,500 feet due north of the Gin. This sandstone apparently pertains to the Wilcox, and it is believed that the central part of the dome is underlain by the Wilcox formation except in the area mentioned as probable Midway and Cretaceous outcrop. Chapman notes that an inlier of the Mount Selman beds is to be found in the central part of the dome, but this was not seen by the writer and, if present, is believed not to be in place.

All of the outcrops along the circular drainage valley which outlines the dome are of soft white, gray, and yellow sandstones and white, purple, and yellow shales of the Wilcox formation. Most of the dip and strike observations recorded were taken on bands of ironstone concretions in sandstones of this formation. The Wilcox formation also forms all of the lower hills and the base of the higher hills which form the outer edge of the circular drainage valley.

The upper part of the higher hills around the outer edge of the circular valley are composed of the characteristic ferruginous sandstones and conglomerates, in places iron ore, of the lower part of the Mount Selman beds, Claiborne, Eocene. The country rock for some miles to the west of this salt dome is of this same formation, though it apparently only caps the hills on the northeast. Hopkins[1] describes a section of the Wilcox in a bluff on the bank of the Trinity River at the mouth of Town Creek, some three miles northeast of the dome.

The dome lies at the easternmost point of a triangular-shaped outlier of Mount Selman beds. Another large irregular outlier of the same formation occurs in northeastern Freestone County. These outliers are cut off from the main body of Cook Mountain—Mount Selman formation, which lies to the eastward in Anderson County, by the broad valley of the Trinity River.

UNDERGROUND GEOLOGY

Some five wells, all comparatively shallow, have been drilled on or around the dome, but available information concerning them is scant and inexact; consequently we can do little but speculate

[1] Oliver B. Hopkins, *op. cit.*

regarding underground conditions. Lee Hager's report of July 7, 1908, on the Blue Lake oil field, states that some three wells had been drilled in the vicinity of Blue Lake up to that time.

The Oakwoods Oil Company is said to have drilled a well to a depth of 800 feet on the J. Strickland tract. A show of oil was reported. Two wells were drilled by the Gum Springs Oil Company, the first reaching a depth of some 1,220 feet and the second a depth of some 600 feet. All of these wells were drilled before 1908 and all of them were drilled in the vicinity of Blue Lake and West Point Mountain. None of them report salt.

At a later date at least two wells were drilled on the southwest side of the dome, one just north of Llewellyn Gin and the other just west of it. No detailed information regarding these wells was obtained. According to local report, the well north of the Gin, where casing still protrudes from the ground, was drilled to a depth of 700 feet and was drilling in rock salt when abandoned. The salt is said to have been struck at a depth of 300 feet.

The only log of any of these wells which is available to the writer is that of No. 1 well of the Gum Springs Oil Company, the deepest of the reported wells. According to Hager, this well was drilled on the east side of the "saline," a name which he gives to the wide valley just south of West Point Mountain. This well was evidently down on the flank of the dome. The log is quoted after Hager's report as follows:

Formation	Thickness in Feet	Depth in Feet
Soil	10	10
White running into dark sand	15	25
Soft slate and lignite	20	45
Alternating hard and soft shaly slate	46	91
Soft very black lignite	45	136
Brown sandy shale	27	163
Blue artesian water sand	71	234
Blue sandy rock	2	236
Brown shale	24	260
Alternating stratas soft coal, brown shale, and crystals of sulphur or paraffins	11	271
Black shale, blue sand with continuous particles of yellow honeycomb rock and strong gas and oil showings	39	310
Black shale	25	335
Black and brown shale, some sand, and pyrites	43	378

Formation	Thickness in Feet	Depth in Feet
Soft coal, brown shale, and pyrites	34	412
Brown shale and bowlders	29	441
Brown shale	25	466
Brown shale, gravel, and pyrites	18	484
Soft rock	2	486
Brown shale, considerable blue sand, and pyrites	31	517
(Missing)	...	....
Brown shale	3	555
Blue concreted sand bearing gas and strong sulphur water	5	560
Alternating dark brown shale, deep blue concreted sand, and considerable pyrites, here passed through 4 inches very hard pale rock, color of limestone, but upon test shows not to be limestone	16	576
Blue concreted sand	10	586
Dark brown gumbo with some black shale and pyrites	19	605
Dark blue gumbo	10	615
Blue sand, shale	2	617
Blue sand gumbo	13	630
Black, very hard shale	25	655
Very hard blue laminated rock	$2\frac{1}{2}''$	....
Blue sand and black shale	3	658
Very hard rock	3	661
Alternating stratas of black gumbo shale with concreted blue sand and numerous iron pyrite bowlders but no rock stratum	559	1,220

Artesian water flowing out of the well was encountered at 163 feet, and oil and gas were encountered from 271 to 319 feet. The gas is said to have had a sweet and pungent odor and to have burned with a blue flame.

Apparently at least the first 400 feet of this log represents the Wilcox formation. Below 400 feet the formations are possibly Wilcox and Midway for 200 to 250 feet, and the remainder of the log represents the Navarro formations.

Aside from the very scant information obtained from the wells, we can only argue by comparison and inference regarding underground conditions.

At the nearby Palestine dome the Midway is believed to be absent, but all of the various formations of the Gulf series of the Cretaceous outcrop in the center of the dome. No continuous section is exposed and consequently the thickness of the various formations cannot be determined.

At the Keechi dome the oldest outcropping formation is the Austin chalk, and the Midway is said to be absent by unconformity. The Texas Company has drilled five wells on the southeast flank of the dome to depths of 3,170, 2,297, 2,656, 2,454, and 3,048 feet respectively. These wells start in the Wilcox, some of them penetrate the Woodbine, and possibly the first well passed through the Woodbine. It is almost impossible to estimate the thickness of the varous formations from the log of these wells.

Near Freestone, about 22 miles S.SE. of the West Point dome, a well was drilled by the Freestone Syndicate, Inc., to a depth of 2,370 feet. This well started in the lower Wilcox or Midway and was evidently in the Eagle Ford when abandoned. The log of this well, according to Lewis C. Chapman, who had the drilling under observation and supervised the collection of samples, was as follows:

Well No. 1, R. A. Tacker

	Thickness	Depth
Wilcox formation	624	624
Midway formation	177	801
Navarro and Taylor formations	820	1,621
Austin chalk	529	2,150
Eagleford shales	220	2,370

This determination is based altogether on lithologic characteristics and is probably exact only for the Austin chalk. The Nacatoch sand member of the Navarro formation is believed to have been passed through from 1,196 to 1,215 feet.

The most exact information regarding the thickness of the various formations in this general region is the section given by Matson[1] and based chiefly on the log of a Magnolia Refining Company well at Corsicana, some 50 miles northwest of the West Point dome. The various formation thicknesses given by him are as follows:

Navarro formation	1,650 feet	2,135 feet
Navarro and Taylor formations	135 feet	
Taylor formation	350 feet	
Austin chalk	425 feet	
Eagleford clay	370 feet	
Woodbine sand	400 feet plus	

[1] G. C. Matson, "Gas Prospects South and Southeast of Dallas," *U.S. Geol. Survey, Bull. 629* (1916), pp. 77–119.

Below the Gulf series of the Upper Cretaceous come the Washita, Fredericksburg, and Trinity groups of the Comanchean, but it would probably require a well more than 3,500 feet deep to reach the uppermost of these formations on the West Point dome.

There is no information regarding the dome material, the salt, gypsums, or limestones of secondary origin, other than the report that rock salt was found at a depth of 300 feet and penetrated to a depth of some 700 feet in the well drilled at Llewellyn Gin. It is not known whether or not there is a cap rock present over the salt.

Structurally this dome is very symmetrical, as is indicated by the dip of the outcropping formations. From one's general knowledge of salt-dome structure he would suspect that the upper part of the salt mass, the intrusion of which gives rise to this structure, has the form of a very regular truncated cone. The very steep dips and outcrop of the older shale (Midway?) formation southwest of Llewellyn Gin indicate that the southwestern edge of the dome is the point of greatest upthrust and consequently the point where the salt lies at the shallowest depth from the surface. The upthrust in this dome has been 800 to 1,000 feet.

The rocks over the top of the salt mass are probably level-lying or nearly so. Around the perimeter the dips are very high, 25°–80°, and away from the center of the dome. They decrease rapidly as one goes away from the dome.

Only the central part of the area affected by the uplift of this dome is shown on the attached map. The entire uplift doubtless has a diameter of 3 to 4 miles and an area of 7 to 12 square miles.

AGE OF DOME FORMATION

The Mount Selman beds of lowest Claiborne (Eocene) age, and the youngest rocks outcropping in this immediate region, dip away from the West Point dome in all directions. Since these beds were involved in the folding which resulted from the formation of this dome, it is evident that the intrusion of the salt mass was not completed before early Claiborne time and the entire process may have occurred at some period since then and down to quite recent time. In fact, the formation of this and similar domes may be a very slow and continuous process now going on.

The West Point dome is a geologic phenomenon so similar to the other interior domes, particularly the nearby Palestine and Keechi domes, that it is undoubtedly of similar origin and probably contemporaneous in formation with them. Deussen[1] argues that these domes "were clearly formed in late Cretaceous or early Tertiary time, as is evidenced very clearly in the case of the Keechi dome of Anderson County, where the Wilcox beds of the Eocene rest unconformably on the Navarro beds of upper Cretaceous, the Midway being absent." He further states that the high angle of dip of the Wilcox around these domes, in conjunction with the unconformity, is plain evidence that the growth of the salt core is the result of different movements at different times.

Hopkins[2] accepts, for the Palestine and Keechi domes, Deussen's theory of the initial uplift of the dome during pre-Midway time and the existence of the domes as islands in the Midway sea. This theory is of course proposed to explain the apparent absence of the Midway formations at both the Palestine and Keechi domes.

This theory is not tenable for the West Point dome, if, as has been suggested, part of the greenish-yellow shales which outcrop west of the Llewellyn Gin are of Midway age. Neither is the theory the only available one, nor, in the writer's opinion, the most satisfactory one, to account for the apparent absence of Midway outcrops at the other domes.

The country rock is very poorly exposed at the Keechi dome and not much better exposed in the Palestine dome. It is entirely possible that a formation composed chiefly of shale and only a few hundred feet thick, as is the Midway, and occurring in a structure where the rocks are dipping very steeply, may not be well exposed or may have been overlooked.

If the Midway is absent in the Keechi and Palestine domes, however, the writer would suggest that it may have been faulted out of the outcropping section by having an older formation, say the Navarro, punched through it from below, and into contact with a still younger formation, say the Wilcox, by the upthrust of the salt core.

[1] Alexander Deussen, *op. cit.*

[2] Oliver B. Hopkins, *op. cit.*

This very peculiar type of structure is common in the Roumanian salt domes, where it has been studied by Mrazec,[1] who has designated the salt-dome structure with intruded and faulted core—his *noyau de percement* or core piercement structure—as "diaper" structure. Deussen[2] describes this very type of "piercement" structure in the Humble field where he regards the "Black Shale" Yegua as having been punched upward through the overlying Catahoula-Fayette sandstone series.

It is the writer's opinion that these domes were formed during very late time. The youngest formations outcropping near the domes have been involved in the deformation resulting from the intrusion or formation of the salt plug in every instance. The extreme youth of most known salt domes is, to the writer, a most significant fact. Sediments of Quaternary, perhaps of recent age, have been involved in the formation of the salt domes of coastal Texas and Louisiana. Pleistocene sediments were markedly folded by the formation of the Mexican salt domes. The mother-formation from which the salt of the Roumanian and Transylvanian domes is supposed to have been derived is of Miocene age and many of the German salt domes pierce Tertiary strata.

All of this points to the extreme youth of salt domes. It is doubtful whether a salt dome whose formation can be established beyond doubt as having occurred in pre-Tertiary time can be cited. This suggests that salt domes are, as the geologic time-scale goes, only transient affairs, and consequently theories of origin implying long life or great age for a dome should be looked upon with suspicion.

OIL AND GAS POSSIBILITIES

The West Point salt dome is believed to be a structure of type suitable for the accumulation of oil and gas deposits in commercial quantities. The upthrust here is not so great as at the Palestine and Keechi domes and it seems probable that the sedimentary formations are less faulted and broken than at those domes. This condition favors the West Point dome.

[1] L. Mrazec, "Les Plis a noyaux de percement," *Bull. Soc. Sci. Bucarest,* 1906: *Monit. due Petrole Roumain,* X (1908), 915–16.

[2] Alexander Deussen, *op. cit.*

The series of rocks forming this structure include known petroliferous or gas-bearing formations as follows: the Navarro formation, Nacatoch sand, is gas-bearing in the Mexia-Groesbeck and Corsicana fields and oil-bearing in the northwestern Louisiana; the Taylor marl includes the oil-bearing formation at Corsicana; the Austin chalk is oil-bearing in the small fields near San Antonio; the Eagleford contains the gas-bearing Blossom sand member of northwestern Louisiana; and the Woodbine sands include oil-bearing formations in northwestern Louisiana.

A test well 3,500 feet deep on the upper part of the flank of the West Point dome should pass through this entire section of rocks.

The direct indications of the existence of oil or gas deposits in this dome consist of the gas and oil shows reported in various wells drilled around this dome, as already stated, and gas seeps and sulphurous water springs near West Point Mountain which have been reported by Chapman and Hager. No search for direct indications was made by the writer, and he is therefore unable to confirm their existence.

None of the salt domes of Texas or Louisiana have yielded gas deposits of marked commercial importance, though many of them have been the source of exceedingly rich oil deposits. None of the interior domes have yet yielded commercial oil production. Some heavy oil (8° Be.) was found in the Woodbine sands on the flank of the Keechi dome in the Texas Company's well No. 1 Barret and Greenwood.

Petroleum in commercial quantities in salt-dome structures of the Gulf coastal plain has as yet been found to occur only under one of the four following conditions: first, in the cavernous limestone and gypsum cap immediately overlying the top of the salt mass, the so-called "cap rock"; secondly, in sands pierced by the salt, abutting against and sealed by the salt, and dipping away from it, the so-called "lateral sands" or "deep sands"; thirdly, in sands or sandstones for the most part lenticular and occurring above the cap rock or the salt dome itself, the so-called "shallow sands" in the Humble, Batson, Spindletop, and other fields or the deep sands in the so-called "deeply buried domes" such as Goose Creek

and Edgerly; and fourthly, in sand lenses and shales on the sides of the dome.

By far the most important of these are the first and second types of occurrence. The fourth type of occurrence might well be included in the same class with the second type except at Humble, where they are quite distinct. The third type of occurrence is much more important than generally recognized and is generally confused with the "cap rock" or the first type of occurrence. Spindletop is a fair example of a field where all of the production, until quite recently, has been supposed to come from the cap rock but where, in fact, much of it has come from shallow sands above the cap rock.

In view of the results obtained in the well north of Llewellyn Gin, which was drilled to the salt without any oil or gas production, and particularly because of the shallow depth at which the salt was encountered, prospects for cap-rock or shallow-sand production on the West Point dome would seem to be very poor. This single well is not a sufficient test of these possibilities, but the shallow depth of the salt is an unfavorable condition.

The possibility of finding oil and gas in the Cretaceous rocks on the flank of the dome has hardly been touched and would seem to justify the drilling of several deep wells. The most attractive area is a circular strip extending around this dome and from the base of the central topographic mound to about a half mile from it.

In view of the failure of the wells of the Texas Company on the flank of the Keechi dome, oil prospectors do not regard the interior domes with much favor at the present time, but these Keechi tests prove nothing but the barrenness of the limited area on which they were drilled. Many salt domes of the coastal group had been prospected intermittently for years before production was found. This is true of West Columbia and Goose Creek, the two most important fields of the Gulf coastal plain today.

The West Point dome shows every surface evidence of being a possible container of oil and gas deposits and should be prospected.

EDITORIAL

JOSEPH BARRELL AND HIS WORK

Joseph Barrell, a younger contemporary of Dutton, Gilbert, Powell, and Van Hise, to name only the most eminent of those upon whose work he built and whom he survived, is outlived by a number of older geologists who recognized in him a rising leader in research, and who feel his loss deeply, as that of a strong, judicious, yet enthusiastic and sympathetic fellow-worker.

Born in 1869, Barrell entered upon his career at a time when the leading minds in geology were opening up bonanzas of fact and theory. Already notable progress had been made in development work. The early prospecting of the Great West which followed the Civil War had been succeeded by the organization of the United States Geological Survey and the consequent co-ordination of studies carried on by able men under the stimulus of companionship in a great opportunity. That companionship, previously divided among small and often antagonistic groups, became general and cordial in consequence of the founding of the Geological Society of America in 1889. Discussion, concession, and co-ordination replaced controversy and opened the way for permanent constructive effort. Barrell fitted pre-eminently into this environment, which emphasized truth and subordinated self.

His scientific life thus coincided with the golden era of geology in America. The brilliancy of its earlier years inspired his studies, and during the last two decades he himself has contributed notably to its advance. Estimating the relative contributions of enlightened nations to geology, he wrote as recently as March, 1919: "For the past generation America, under which name should be included both the United States and Canada, has held a position of world-leadership in that science." The place which he himself filled in that leadership his contemporaries cannot justly estimate. But there is unanimous recognition of the fact that he was one of the strongest of the younger leaders and a man of great promise.

Lehigh University trained Barrell. He received three degrees, Bachelor (1892), Engineer (1893), and Master (1897), from that institution, took the degree of Doctor of Philosophy at Yale in 1900, and was honored by that of Doctor of Science in 1916 by his Alma Mater. Prior to his studies at Yale he had both taught and practiced mining engineering, and he continued to be an engineer when he became a geologist. His reasoning is stamped with the precise habits of thought which distinguish the practical from the theoretical. It is told that he would often draw a diagram before he wrote a statement.

Barrell pursued geology with ardent scientific interest from 1898 on, and thus gave a score of years of the prime of his life to it. As assistant in field work of the United States Geological Survey (1899–1901) and as a teacher of the natural sciences, especially of zoölogy and geology at Lehigh (1900–1908), he prepared himself for advanced research in its greater problems, and while occupying the chair of structural geology at Yale (1908–19) he found the larger opportunity to develop his especial abilities as an Engineer of Science.

The phrase engineer of science is used with all regard and respect to distinguish Barrell's activities from those of his great associates, who are better known in the field of theoretical investigation. It is a prime function of the engineer to test assembled materials, in this case facts, before proceeding to build with them firm structures, in this case logical conclusions. His work is kept by professional standards within limits which are fixed by quantitative values. Excursions into the realm of theory beyond those limits Barrell allowed himself only in his latest thought. In so doing he gave evidence of a tendency to develop from the engineer into the natural philosopher, whose thought transcends analysis as imagination transcends mathematics. The great loss to science in Barrell's death is that this evolution of mind from so fertile a source was cut short when there was yet promise of a score of years of productive growth.

The engineer in geology is strikingly illustrated in Barrell's first important contribution to the science, an article on the relative importance of continental, littoral, and marine sediments. He set forth his method of studying sedimentary structures and their

origin as comprising, first, discussion of the conditions of formation of sediments; second, comparison of the areal and volumetric importance of the several kinds of deposits now forming; third, consideration of the probable changes in relative importance which may have occurred in the past; and fourth, presentation of detailed distinctions by which the several deposits may be recognized, with a view to separating and interpreting them in terms of geography and climate.

It may be said that this is the sound scientific method of proceeding from facts to interpretation. It is also sound engineering. It builds permanent structures. By means of it, in the paper referred to and by others in which he applied the distinguishing criteria of sedimentation to specific examples, Barrell made an important and essentially original contribution to geology in that he forced the recognition of continental, fluviatile, and eolian sediments among stratified rocks which had been previously regarded as of marine origin exclusively. He thus revolutionized the criteria of paleogeography and paleoclimatology.

Paleoclimatology is a field to which Barrell unlocked the gate, if indeed he may not be said to have discovered it. His article on relations between climate and terrestrial deposits traces the complex variations of temperature and rainfall and their effects upon sediments with such keen analytic power, such wealth of illustration, and such logic as to lay firmly the foundations of interpretation of terrestrial stratigraphy in terms of climate.

Among the great problems of the past thirty years in geology and geodesy there is none more congenial to a mind like Barrell's than that of the strength of the earth's crust. His investigation of the subject illustrates the conscientious thoroughness with which he did his work. He was so serious, so earnest in investigation, that he could not leave any aspect of a subject untouched. His presentation is therefore an exhaustive review, analysis, and critique of the contributions previously made, together with a statement of the deductions which he found reasonable. He attacked the complexities of the subject, not only as a geologist and engineer, but also as a mathematician. He did not hesitate to enter the lists against those who arm themselves with higher mathematics and who seem invulnerable to attack by geologists

unfamiliar with the weaknesses of their armor. In the *Strength of the Earth's Crust* Barrell demonstrated the character and quality of his mind. He was a great analyst.

It is of interest to contrast Barrell's method with Gilbert's in the discussion of the fundamental problems of isostasy. Gilbert was a co-worker with Dutton in the studies that gave birth to the concept. Dutton formulated the idea of isostasy in 1889, and Gilbert discussed the related problem of crustal strength in 1890 in *Lake Bonneville*, the manuscript of which, so far as it touched this subject, was under consideration in 1888 and earlier. Gilbert's last contribution to the subject was in 1913. It is a brief but comprehensive interpretation of anomalies of gravity. In the interval of twenty-five years he wrote but little on isostasy, although he was associated with Putnam in the initial studies of gravity intensities in the United States and followed Hayford's brilliant work with constant interest. He published far less in a quarter of a century of investigation than Barrell has given us in one group of articles. Barrell's analysis covers every part of the subject exhaustively, dissociates all its elements, weighs them, and recombines them. It is the product of extraordinary industry, activity, and thoroughness. Gilbert, a profound thinker, a philosopher, awaited patiently the unfolding of knowledge. He entered into no controversy. Nothing escaped him, but he was content to sketch the edifice of truth in terms of fundamental principles. He anticipated Barrell in conclusions as to the relative importance of rigidity and isostasy, which the latter's exhaustive analysis confirmed.

A work comparable in exhaustive treatment with Barrell's *Strength of the Earth's Crust* is his *Rhythms and Geologic Time.* Rhythms in denudation and rhythms in sedimentation are discussed through sixty pages, emphasis being laid upon the pulsatory character of uplifts and subsidences. In contrast to previous discussions the view is developed that "the deposition of nearly all sediments occurs just below the local base level, represented by wave-base or river-flood level, and is dependent on upward oscillations of base level or downward oscillations of the bottom." If this be so, it follows that there are numerous interruptions in the process of sedimentation, some of which are already known as

disconformities, while to others of lesser duration in general Barrell would apply the term "diastem." The recognition of diastems and disconformities greatly lengthens the estimates of geologic time based on sedimentation. This discussion is followed by a review of all previous estimates of geologic time, distinguishing those based on oceanic salts and on radioactivity. The latter is fully and favorably presented. The paper closes with a section on the convergence of evidence, in which the physical terrestrial phenomena are compared with those of biologic evolution and stellar evolution. The trend of the argument is toward the acceptance of a very great age for the earth, possibly fifteen hundred million years. But, on the other hand, the amount of solar energy due to gravitational infall is found to be but approximately 1 per cent of that which would have been radiated during that immense lapse of time, and Barrell is thus led to consider the probability that there are other sources of energy in the sun than gravitational condensation. He recognizes that the great concentrations of energy must have previously been stored, and concludes: "The scheme of the universe is more profound and the unknown is a little nearer than it was recently thought to be."

The planetesimal hypothesis of the genesis of the planets has taken a permanent place among the foundations of geologic theory in America. Reviewing Chamberlin's *Origin of the Earth* Barrell wrote:

> To gain a proper appreciation of the value of the investigations which are condensed in this volume we must compare the present state of thought upon the general subject with that of twenty years ago, before Chamberlin had begun to publish upon the hypotheses of earth-genesis. Measured by that perspective, this volume is seen to represent an advance in thought on this subject so great that the names of Chamberlin and Moulton must rank high among those scientists who have dealt constructively with that vast, vague, and remote problem, the origin of the earth. The subject of earth-genesis is now fairly on the road to scientific investigation in place of philosophic speculation.[1]

It was characteristic of Barrell that he should translate the thought of the last sentence into action and should proceed to investigate the subject of earth-genesis by applying tests to Chamberlin's hypothesis, or rather to the group of multiple hypotheses, some of which were adopted and some discarded by Chamberlin in

[1] *Science*, 1916.

reaching the final, most reasonable, conclusion, as he saw it. However, in judging alternatives, there are many opportunities for divergence of opinion, and among those which are offered in this particular case Barrell has seized upon the one which is most significant in separating two distinct lines of geologic inference: Did the earth grow up as a comparatively cold, solid globe, or did it become molten and cool down from that condition? The question turns upon the size of the planetesimals and their manner of infall. We may best let Barrell state the alternatives by quoting from a lecture delivered by him at Yale in November, 1916:

Under the terms of either nebular or planetesimal hypothesis a scattered state of the planetary material is implied as a stage antecedent to the origin of the planets. Was this growth of the planets geologically slow or rapid? Did it take tens or hundreds of millions of years, or was it on the contrary largely accomplished in tens or hundreds of thousands of years? Was the material largely in dust-like or molecular form or was it to a large extent in nuclei of considerable size? From these different postulates very divergent consequences may be traced in the formative stages of the earth; and finally the present nature of the earth itself may speak in favor of one or the other of these views.

Chamberlin adopts the hypothesis that the stages of earth-growth were very prolonged, even geologically speaking, and that the accretion was dominantly of dust-like or molecular particles. According to him the building up of the planets followed three stages: first, the direct condensation of the nuclear knots of the spirals into liquid or solid cores; second, the less direct collection of the outer or orbital and satellitesimal matter; third, the still slower gathering up of the planetesimal material scattered over the zone between adjacent planets. This third factor in Chamberlin's view is regarded as very important, and he believes this diffused matter contributed much of the earth's substance, very slowly and in dust-like form. This is one of the critical points in the details of the theory upon which turns much of the development of the following argument.

Chamberlin conceives the earth to have been built up as a solid body, not to have been fluid or viscous at any time later than the early nuclear stage, and to have begun to hold an ocean by the time it contained thirty or forty per cent of the present mass. Such liquid rock as was generated by compression or radioactivity during earth-growth is regarded as having been kneaded and squeezed to the surface, where it solidified approximately as fast as it was formed. In earth-growth the denser planetesimal dust, he argues, tended to be somewhat segregated into the primitive ocean basins, and served to maintain in them, as the earth was built outward, a greater density than in the elevated zones between, establishing thus a relation between density and elevation.

It seems a debatable question if such a large proportion of the added material was necessarily dust-like and capable of being weathered, sorted, and distributed by the primitive atmosphere and ocean. . . . . In fact, from this beginning of earth-growth the preponderance of the evidence appears to the writer to be against those sub-hypotheses which Chamberlin has followed. This evidence, its bearings, and conclusions will form the following parts of this article. It will be of ultimate value to both lines of argument that each may be weighed against the other. . . . .

It appears to the writer that the chemical character of the igneous rocks, the limited depth of density variations in the crust, the limited amount of salt in the sea, the rotation period for the moon and planets, all point to a molten condition of the earth at the completion of its growth. . . . . The questions raised by this conclusion are: What mode of growth would have favored the molten state and how far did this precede the beginning of the geologic record as given by the oldest rocks exposed at the surface of the globe ?[1]

Barrell then proceeds to discuss in terms appropriate to a lecture rather than to an analysis, as the occasion demanded, the significance of the planetoids, the indications of primordial tidal retardation, and the deductions which may be drawn from the limited amount of oceanic salt as to the age of the ocean. Condensed though it is, the argument is too long to be quoted here, but the description of the early stages of the earth, as Barrell conceived them, sheds light upon the tendency of his mental development:

The indications of primordial tidal retardation and the limited amount of salts in the sea both point to the conclusion that the earth was molten at the completion of its growth. The molten state suggests a rapid earth-growth due to an original clustering of the matter whose convergence built up the planet. Larger nuclei, hundreds of miles in diameter, and smaller ones comparable to the planetoids, moved in elliptic and nearly intercepting orbits. Mutual perturbations kept modifying these orbits and providing new chances for collisions, union, and growth. Such collisions led to a development of energy of impact sufficient to produce in the growing earth a molten state at least in the outer portions. The earth kept growing at the same time by sweeping up large quantities of finer material, but a molten state suggests that the greater growth was due to the infall of the larger nuclei. Finally but one outstanding nucleus, the moon, was left beside the earth, and the earth-moon system attained a condition of stability and completed growth.

After describing the state of the molten globe, which he conceives to have been surrounded "even in its molten stage by an

[1] The first of a group of lectures delivered before the Yale chapter of Sigma Xi during the academic year 1916–17, entitled "The Evolution of the Earth and Its Inhabitants. The Origin of the Earth," by Joseph Barrell.

envelope of water in the form of a deep and heavy atmosphere of water gas," forming an effective thermal blanket, Barrell continues:

> The effectiveness of the blanket depended upon the peculiarity of both water gas and carbon-dioxide in being opaque to the slow vibrations of dark heat, absorbing these near the bottom of the primitive atmosphere and re-radiating them from higher levels as long, slow heat waves. Strong convection currents carried up these heated gases from the superheated base to the higher levels of the atmosphere. There the chilling condensed the water vapor into a thick and universal canopy of cloud, boiling up like thunder heads from below, shedding continuously a downpour of acid rain, rain dissipated again into vapor as fast as the drops fell into the deeper and hotter strata of the atmosphere. The intensity of the vertical convection maintained a high electric tension. Incessant flashes of lightning linked as with living fiery tentacles the cloudy heavens to the lurid molten earth. Tremendous reverberations of thunder, unsensed by mortal ears, shook the atmosphere in the world-wide primeval storm. . . . .
>
> During the more rapid growth-stages the molecular and dust-like matter swept up by the earth settled like a never ceasing cloud of volcanic ash. The planetesimals of sand and gravel size were swept up by the earth many millions of times more abundantly than our meteors at the present time. Those meeting the earth with the higher velocities were consumed by impact. Over the hemisphere of night the otherwise invisible atmosphere above the cloud canopy scintillated with incessant flashes of light and trails of luminous dust. Bodies of larger size gave in their dissolution a still more brilliant display and penetrated to greater depths. At longer intervals, with Titanic rush and roar, a greater projectile, tens or even hundreds of miles in diameter, cleaved through the canopy of cloud, leaving a tumultuous maelstrom behind, drove almost unchecked through the dense atmosphere below, and, with world-wide commotion, was engulfed with development of fervid heat, within the molten sea.

Only he who has a sure grasp on the controls can safely essay a flight of the imagination where the conditions so surpass all experience. Barrell's earlier, intensely analytical work showed little evidence of the power of philosophic speculation, the scientific use of the imagination, which is nevertheless the parent of investigation, even as Chamberlin's thought is the father of Barrell's. Barrell would have fallen short of the full stature of the philosopher if he had not developed beyond the engineer. Such passages as those quoted above show that he had grown in imaginative power, and, being severely controlled by the logical habit of thought of his early engineering and scientific career, he would have used that power judiciously, greatly to the advantage and advancement of

science. His death has robbed us at the moment when his promise was greatest.

Barrell's work is not yet done; his service to science and to his fellow-men is still incomplete. He has left it in our hands and in those of the younger generations to come. His research, which he loved, is to be carried on. His example, which is inspiring, is to be followed. We may well ask, as suggested by Dr. Branner, How are young men to be trained up to become Barrells? His mental qualifications were not extraordinary. His schooling was not unusual. Yet he became a most unusual man.

The reason for Barrell's strength can be expressed in two words, thoroughness and breadth. Whatever Barrell did he did thoroughly. The articles cited in this memoir demonstrate that fact. But let it be borne in mind by any young man who would aspire to be like him that such thoroughness is a habit of slow growth. He who would possess it must begin soon and must determinedly will to be thorough. Barrell studied thoroughly, acquired knowledge thoroughly, so that he knew what he knew, not for today or tomorrow only, but for his lifetime. For that reason he was able also to be broad.

Breadth and thoroughness of knowledge are often considered incompatible, and it is true that thoroughness and specialization are commonly associated. But thoroughness in laying foundations is the basis of great breadth of superstructure. Barrell was thorough in acquiring the elements of mathematics, chemistry, physics, geology, meteorology, astronomy, and zoölogy. He knew well the general principles, the broad facts, the methods of each science. He was firmly founded in them. Thus, when he had occasion to study climates of the past he approached them with an understanding of climates of today. When he would discuss the strength of the earth he could command his mathematics and mechanics. When he undertook to explore the unknown realms of earth-genesis he was equipped with an understanding of astronomy and physics that supplied the seed from which to grow his tree of knowledge. When he gave his imagination flight it was on wings of strength that it soared, giving us confidence that it could soar safely and to great heights, whence the profound depths of the unknown might be searched.

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